EXPOSURE ASSESSMENT PROJECT AT

The Paducah Gaseous Diffusion Plant

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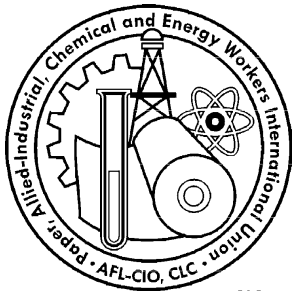

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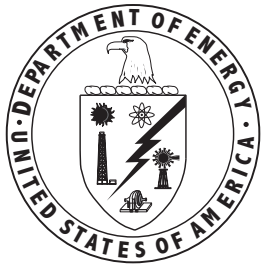

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Figure F-2. Schematic diagram of Building C-315 Tails Withdrawal Area.

Figure F-3. Schematic layout of a cascade converter or cell with associated compressor.

Figure F-4. Schematic layout of a cascade consisting of 5 converters.

EXECUTIVE SUMMARY

PURPOSE AND APPROACH

The Exposure Assessment Team (herein referred to as the "Team") was charged with conducting a preliminary study at the Paducah Gaseous Diffusion Plant (PGDP) to define the radiological issues, the categories of workers that may have had increased potential for radiation exposure, the locations and processes where increased exposures may have occurred, and, where possible, provide some reasonable estimates of radiation exposures to the worker groups. While all types of possible radiation exposures were considered, particular attention was given to potential exposures to the transuranic elements (TRU), neptunium and plutonium. Dosimetric information on worker exposures to the transuranics was particularly meager.

LIMITATIONS AND CAVEATS

The information and data used in this report were obtained from readily available documentation and from an electronic database of worker exposures. The electronic data was used in the initial identification of general worker groups and categories that may have been at increased potential risk for radiological exposures. There are notable limitations to the data. Analysis based on these data should therefore be considered preliminary and unverified. Lifetime doses for workers who received internal radiation exposures prior to 1989 were not included in the data. The electronic database containing worker exposure records had not undergone a quality control evaluation, and has not been verified against the original written documents. The Team notes a number of instances where the data in the electronic database are not consistent with original documents and it does not encompass all dosimetry records over the history of the operation of the plant. In particular, the electronic database contains no transuranic urinalysis results prior to 1989.

The Team recommends the conduct of a quality assurance/quality control (QA/QC) check of the electronic databases used for this report. This QA/QC check should compare the databases with the original, hard copy worker radiation exposure records to better determine the overall accuracy of the database and implications to the outcome and conclusions of this report.

Plant records, reports, memorandums, and other written documents including reports in the media were also used to develop this report. The Team critically assessed many of the early reports, memos and prior studies done at the plant. There were, however, many gaps in the written records. For example, health physics monthly reports from the early 1950's and many in the 1960's and 1970's were not obtained. The recorded recollections of the workers (worker transcripts) were particularly important in the development of worker radiation exposure profiles and exposure scenarios and in assigning general risk categories to the worker groups.

The Team made preliminary assessments of potential internal exposures in areas identified as having significant transuranic source terms. The assessments are based upon available area air

monitoring results and the conservative assumption that no respiratory protection was used. This was an "exposure assessment" and not an "exposure or dose reconstruction." The limited PGDP job/task/area exposure assessments provided in this report are indicative of potential exposures only and should not be construed to represent an actual exposure to any individual worker.

The Team recognizes that radiation exposures to some of the workers were likely "missed" for a variety of reasons that include: lack of documentation; failure to monitor or adequately detect the exposure; lack of sensitivity of the technique to assess smaller doses; or failure to recognize a radiological hazard. The Team feels that at this time there is inadequate verified information to quantitatively assess these "missed doses" for the plant-wide population of the workers. However, a qualitative recognition of these issues is considered in this report.

Finally, the Team only had a very limited time frame with limited resources to perform this initial evaluation. New documentation and new information were received even as the report was being finalized and all information, some of it potentially important, could not be reviewed and included in this report. For this reason, this report must be considered as a "preliminary" document.

This report classifies the potentials for increased radiation exposure as "low", "moderate", and "high." These classifications are based on perceived hazard by the team and only indicate relative hazard, not necessarily any quantitative hazard (i.e. a "high" potential does not imply a "high" dose).

As noted earlier, this report is based upon available interviews and documentation. When assumptions were made or models adopted to support the exposure assessment process, they were so stated in the report.

PGDP RADIOLOGICAL CONTROL PROGRAM

Recent reviews of the PGDP were conducted and were published as the "Phase I" [1] and "Phase II" reports [2]. The Phase II report [2] noted that the health and safety programs, although minimally staffed throughout much of PGDP's history, were always in place. Line supervisors and not the health physics personnel were responsible for implementing and monitoring industrial and radiation safety programs for the workers. Also, it was noted [2] that the programs were not based on the concept of keeping worker exposures As Low As Reasonably Achievable (ALARA). The DOE Phase II report noted, "In the early years of the plant, many of the potential radiological hazards were either not recognized or not fully appreciated."

Personal external radiation monitoring (using film badges and later thermoluminescent dosimeters (TLDs)) and an *in vitro* bioassay program (primarily focused on measuring levels of uranium in the urine) were in place from the beginning of plant operations. In the early years (1953-1960), it is apparent that these programs focused on those workers believed to have the greatest potential for increased radiation exposures. After 1961, the programs were expanded to include most workers. In addition to the dosimetry programs, air sampling was performed in most process buildings. The methods included fixed-head area air sampling along with some spot air sampling of specific jobs.

The team reviewed limited information pertaining to work conditions in the plant over time. Specifically, past health physics and hygiene reports, health physics inspection reports, and worker interviews were useful in getting a better description of work conditions. Additionally, the DOE Phase II report [2] provided a description of work conditions over time at the PGDP. The contamination control program was considered by the Phase II report to be "ineffective" through the mid 1980's [2]. Reports of extensive contamination in lunchroom areas [3,4], workers covered with black soot subsequent to ash handling operations [5], C-410 floors routinely covered with visible green powder [3,6], and surveys indicating elevated concentrations of transuranics in almost all process buildings [7,8] illustrate some of the inadequacies of the contamination control programs.

Personnel protection equipment was available, but some workers report that this equipment was not always used or when used, not always used appropriately [2]. Reports from workers along with information from health physics inspection reports indicate that respirator use was at best "inconsistent" and often considered "voluntary"[2]. Additionally, there were reports that frequently, contamination levels found on workers' personal clothing were above release limits [2].

RADIOLOGICAL HAZARDS AT THE PGDP ¾ EXTERNAL EXPOSURES

In general, the workers with increased potential for external radiation exposures (e.g., gamma rays and beta particles) were performing tasks or were in locations where they could potentially receive increased internal radiation exposures (e.g., inhalation of uranium, plutonium and neptunium). In general, external radiation exposures were monitored using methods appropriate for the time, although in the early years of the plant, some worker groups may not have been monitored and/or were not recognized as being at risk. From 1952 through 1960 approximately 200 to 500 workers were monitored for external radiation exposure. In 1961, the program was broadened and all workers (approximately 1700) were monitored. Dosimetry results obtained after the program expansion show that previously unmonitored groups of workers might have received "missed doses" during the early years of plant operations. The monitoring methods included the use of film badges and later TLD badges. Some workers stated that some higher badge readings were assumed to be invalid and were thus discarded.

Based on exposure records in the database, worker interviews and health physics and inspection reports, it is estimated that approximately 2,500 to 4,000 workers worked in areas with "moderate" to "high" potential for increased internal and external radiation exposures. This is based on a relative ranking of the potential of radiation exposures at the PGDP. These areas included the Feed Plant (C-410/420), Decontamination Building (C-400), Metals Building (C-340), and the Cascade Buildings (C-331, C-333, C-335, and C-337). Primary Departments identified included: Process Operators, Chemical Operators, Maintenance Mechanics, Instrument Mechanics, and Electricians. The Team identified some hardcopy exposure data that was either inconsistent with or not included in the unverified electronic database.

From the written and electronic records, it is apparent that there was a potential for increased external radiation exposures in Buildings C-410/420, C-400, C-340 and C-720. Although only one exposure record in excess of 5 rem in a calendar year was identified in the provided electronic

database, these data indicate that there were approximately 200 individuals, who received in excess of 1 rem external exposure in any one calendar year. The Health Physics reports also document that many workers exceeded the weekly plant action level of 300 mrem/week, but suggested that workers were kept below the annual regulatory limits by rotation of duties and limitations on stay time in higher exposure areas.

RADIOLOGICAL HAZARDS AT THE PGDP ¾ INTERNAL EXPOSURES

The internal dosimetry program at the Paducah plant primarily focused on routine uranium urinalysis and for the most part, internal exposure to uranium was considered to be a chemical rather than radiological hazard. A 1960 memorandum did raise issues relating to neptunium exposures and stated that there were "possibly 300 people at Paducah who should be checked out [for neptunium exposures]". The memo also stated "they hesitate to proceed to intensive studies because of the union's use of this as an excuse for hazard pay."[9]. Early Health Physics and Hygiene reports indicate some limited *in vitro* bioassay monitoring for neptunium and plutonium exposures as early as 1959 [10]; however, the provided database contained no urinalysis results for these isotopes prior to 1989. No routine *in vitro* monitoring for neptunium was apparent prior to 1989.

Some *in vivo* monitoring (lung and whole body counting for uranium and neptunium-237) was performed. The electronic database included records from 1969 forward, although it is apparent that earlier paper records exist. The Team questions whether some of the early methods used in these studies were sensitive enough to detect significant internal depositions of radioactive materials in workers. It should be noted that historic documents indicated concern regarding exposures to other radionuclides (technetium, ruthenium, etc.) [11,12], however there was inadequate information available to assess these potential exposures.

There were a number of discrepancies and inconsistencies noted in the uranium urinalysis program data that were available to the Team. For example, within health physics reports there were several documented incidents (from 1950-1986) where elevated urine results were reported, but these results were not included within the electronic database. Additionally, some workers reported practices regarding the implementation of the urinalysis program that may have been inconsistent with procedures of the time and may have resulted in undetected intakes of radioactive materials. Nonetheless, the urinalysis database was used along with Health Physics summaries, and worker interviews to help identify departments that had greater potential of having internal radiation exposures.

Based on ICRP methodologies and several sets of generally conservative assumptions, some internal dose estimates for neptunium-237, plutonium-239, thorium-230 and uranium were made for selected jobs. The dose estimates were made based on available historical gross alpha air sampling data along with estimates of the radionuclide percentages characteristic of certain operations. Internal dose estimates were only calculated for operations identified as having an increased potential for transuranic exposures and for which area air sampling data were available. Surveys, performed as recently as 1991, indicate transuranic materials in many of the process buildings at the site. This raises the possibility that other groups of workers may have been exposed to these materials.

It was determined that some workers could have had internal radiation exposures that may have exceeded regulatory limits. This may include on the order of 10% of the 2,500 to 4,000 workers with the potential for increased radiation exposures. Some of the areas where workers were more likely to have had increased internal radiation exposures included C-400, C-410/420, C-340, C-720 Converter Shop and Cascade Maintenance. As noted above, these areas were generally the same as those areas with the potential for increased external radiation exposures.

POTENTIAL DIRECTIONS FOR FUTURE WORK

The Team particularly encourages a verification of the electronic database against available original, hard copy dosimetry records. In addition, verification of both the accuracy and the completeness of the database would be essential prior to any attempt to further assess individual worker exposures.

Internal radiation dose estimates based on available air sampling results and assumptions regarding radionuclide percentages are presented in this report. To ascertain that these calculations are reasonable, it is recommended that available pre-1989 transuranic and thorium bioassay monitoring records be obtained and depending on the adequacy of these data, doses be calculated.

Further, the Team notes that there have been many advances in retrospective dosimetry techniques that may be useful in determining past radiation exposures. These include, but are not limited to, bioassay methods such as fission track analysis (FTA), thermal ionization mass spectroscopy (TIMS), accelerator mass spectroscopy (AMS) and inductively coupled plasma mass spectroscopy (ICP-MS); whole body counting techniques and molecular methods, such as fluorescence *in situ* hybridization (FISH) and electron paramagnetic resonance (EPR) methods, using tooth enamel for estimating total body lifetime external exposures. The team recommends that a feasibility study of these techniques, including an assessment of the current capabilities and the applicability of these methods for purposes of retrospective dose assessment at the PGDP site, be conducted. The strengths and limitations of these techniques must be considered prior to their application and use for any future dose exposure assessment and/or dose reconstruction.

1.0 INTRODUCTION

Synopsis *¾ Due to concerns about the present and historical worker health and safety programs at the Paducah Gaseous Diffusion Plant (PGDP), the Team was commissioned to perform a preliminary evaluation of the historical potentials for worker radiation exposure and numbers of workers that may have had the potential to be exposed. Previously, a DOE Headquarters Office of Oversight team had issued a report of the historical safety conditions at the PGDP, the so-called "Phase II Report". Of particular interest to the Team were the issues relating to the transuranium elements (also called "transuranics" or TRUs), mostly isotopes of neptunium (Np) and plutonium (Pu). The general scope of the study conducted by the Team was to define the radiological issues, the categories of workers that may have had increased potential for radiation exposure, the locations and processes where increased exposures may have occurred, and, where possible, provide some reasonable upper and lower boundaries of radiation exposures to the worker groups. The team was also charged with evaluating the feasibility of conducting new analyses, including bioassays and radioassays.*

The data presented in this report is considered preliminary in nature. Due to time constraints, data used during this assessment came from only readily available sources and much of the information used has not been verified against original records. The dosimetric information in particular should be viewed as preliminary and will certainly change as more information is obtained. Additionally, dose information was not collected for any individual workers, only groups of workers by occupation, location or "department".

Given the quality of the worker radiation dose data that was available, and the time and resources for this study, it was only feasible to group quantities related to worker radiation doses by selected occupations, locations or "departments." No attempt to calculate individual worker lifetime radiation doses was made. Given the uncertainty in currently available worker radiation dose data, extrapolation of this limited information to estimate the risk of possible health impacts to workers was felt to be premature at this time. The purpose of this study was to determine a range of possible numbers of workers, types and locations of work and the possible radiation dose from the introduction of recycled uranium into the feedstock that was shipped to Paducah for processing. This report satisfies its stated purpose. Workers may wish to participate in the recently approved Title XXXVI – "Energy Employees Occupational Illness Compensation Program" to determine if any adverse health impacts, from their work at Paducah, are job related and compensable. Those workers interested in the Compensation Program should call, toll free, (877) 447-9756.

1.1 Background

During 1999 there was a growing public awareness and concern about present and historical environmental, safety and worker health issues at the Paducah Gaseous Diffusion Plant (PGDP). In response to these allegations, the Secretary of Energy initiated an investigation at the PGDP. The radiological issues included possible inadequate radiation controls for worker exposures, the presence of transuranic materials (those elements with atomic numbers greater than uranium) in

concentrations greater than previously thought, and the failure to adequately inform the workers of the potential hazards. Of particular concern was the presence of transuranic (TRU) materials that included neptunium and plutonium.

The initial DOE investigation reviewed operations at the plant from about 1990 to the present. A report was issued in October, 1999 ("Phase I") which identified a number of current environment, safety and health issues at the plant that are under the auspices of the DOE [1]. This review was followed by a more detailed investigation of historical operations. The results of this investigation were published as the "Phase II" report [2]. The issues addressed in the Phase II report include historical operations, activities, workplace conditions and hazards at the plant. A number of workers were also interviewed to assess their concerns, and their understanding and knowledge of historical plant operations and hazards. The Phase II report also includes a review of some of the management practices relating to regulatory controls and standards in place over time, and identified a number of radiological issues related to worker radiation exposure that will be reviewed in greater detail in this report.

Concurrent with the commissioning of the investigation teams, other teams were assembled or programs augmented. The medical surveillance program that had been established prior to August 1999 was further supported and is to continue to evaluate and monitor worker health effects at PGDP and other gaseous diffusion plants including Portsmouth and the Oak Ridge K-25 Gaseous Diffusion Plant. This program is being conducted by the Paper, Allied-Industrial, Chemical and Energy Workers International Union (PACE), Queens College, and Creative Pollution Solutions, Inc. (CPS).

The Team responsible for the present report was assembled in January 2000 and included the University of Utah, PACE International Union, and CPS as participating members. The members and participating institutions of the Team may be found in Appendix A. A listing of the abbreviations and acronyms used in this report is found in Appendix B.

1.2 Scope and Approach of Assessment Project

The Team, which includes members from the University of Utah, PACE International Union, and CPS, was charged with the following general tasks:

a) Collect, evaluate, review and index relevant historical and contemporary documents relating to radiation exposures at the Paducah Gaseous Diffusion Plant (PGDP). The documents that were used in this report are included in the bibliography.

b) Identify radiological issues that may affect or have affected worker health and safety. This information has come from recollections of current and former employees, plant and union personnel, plant design, production, process and sites evaluations, occupations and duties and processes. The team has also evaluated the electronic archive of exposure records to help identify the numbers, occupations and types and magnitudes of radiation exposures.

c) Identify, retrieve and evaluate radiological records and *in vivo* and *in vitro* bioassay results. Plant records were used in this report to identify areas, locations, occupations and/or worker groups who may have had the potential for increased radiation exposures.

d) Evaluate the feasibility of conducting a bioassay program. The feasibility of conducting a bioassay program to establish with a reasonable certainty the body burden of plutonium and perhaps-other nuclides in workers was considered. Technologies useful in such bioassays are summarized.

e) Evaluate the feasibility of conducting radioassays of residual materials. In the event that suitable materials were identified and became available, the feasibility of performing radioassays on these materials was to be evaluated.

f) Develop occupational exposure profiles. From the data and information generated from the other Tasks, exposure profiles and scenarios were created that would provide realistic and scientifically defensible worker radiation exposure ranges along with the numbers of potentially exposed workers for the identified areas or work groups with the potential for increased radiation exposure at the PGDP. The limitations and assumptions used in the development of these potential exposure profiles are presented.

The Team is composed of a variety of members with rather broad radiological and radiobiological expertise. The Team agreed with the philosophy to approach this assessment project using a contemporary scientific approach that includes thorough review and documentation of findings, critique and discussion, and a healthy skepticism of the data.

1.3 Data Considerations and Caveats

The Paducah Gaseous Diffusion Plant has been in operation since the early 1950's. To locate and review the historical and contemporary documents associated with the operation of the plant is a daunting task. Many of the documents that were obtained were not written to address a scientific audience; rather they were produced for managerial purposes. Thus, the lack of scientific and technical detail in many of the historic documents contributed to the challenge. Citations are provided in the current document, and the bibliography represents the documents and information that were available at the time. The Team did not review classified data. Some of the processes, procedures, and equipment remain classified and thus could not be fully evaluated.

All of the dosimetric information was obtained from the various available electronic databases or reports and these data have not been verified with the original hard copy records. A 1991 memo from Martin Marietta Energy Systems to ORAU [13] states that "ORNL has been reassessing many previous internal exposures in light of the current DOE Order and has found that data stored on the history tapes provided to ORAU may be inadequate for dose assessment. Use of the original hard copies of bioassay results was found to be necessary." The memo went on to state that "data stored on the history tapes prior to 1989, particularly those associated with internal exposures, were for compliance purposes only and may not be sufficient for dose assessment." The Team confirmed that some original data were either missing or inconsistent with the provided

electronic database. Additionally, there were reported statements from several workers challenging the validity of some of the dosimetry records [14].

The Team recommends that QA/QC checks on the electronic database be performed to allow for a more comprehensive assessment of the radiation exposed worker population or cohort. This database was used by the Team but with the common understanding that this record is not complete and contains many omissions and inaccuracies. The database has not undergone any quality control (QC) or quality assurance (QA) evaluations and has not been checked against the original paper records. A QA/QC check of these worker radiation exposure electronic databases is to be conducted as part of the exposure assessments at the other gaseous diffusion plants in the Department

There are a number of reasons why exposures may have been "missed". Some of these include the lack of documentation for an exposure, the failure to monitor or adequately detect the exposure, the lack of sensitivity of the technique being used and the failure to recognize the radiological hazard. From the worker interviews, it was apparent that many or all of these might have occurred. Various scenarios can be constructed to estimate "missed doses", but the Team feels that at this point there is insufficient verified data or information to quantify these "missed doses" in a scientifically defensible manner. However, qualitative evaluation of these issues and their relative impact on exposures can be performed.

Of primary importance in this evaluation are the potential exposures to and risks from the transuranics (TRUs), particularly neptunium and plutonium. It is now known that these elements were present in the plant, often concentrated in some processes and plant locations. The data made available to the Team on the actual concentrations of the transuranics in the process or at plant locations is meager. Early Health Physics reports indicated that limited bioassay monitoring for neptunium and plutonium was performed [10], however, the electronic database provided to the Team contained no urinalysis results for either plutonium or neptunium prior to 1989. Thorium-230 may also be a significant, but previously inadequately assessed, source of internal exposure. There have been few direct measurements of these materials in any of the workers and thus the estimation and calculation of potential exposures and doses are considered preliminary and have considerable uncertainty.

The Team also recognizes that there were a number of potential sources of radiation exposure at the plant or in materials that were brought to the plant. This report does not encompass all possible sources of exposures, types of exposures, locations of the potential radiological exposure, and worker exposure scenarios. Some of the types of exposures that have not been extensively assessed to date include neutron sources, fission products other than technetium, uranium daughter products and thorium.

1.4 Report Structure

The body of this report contains the general narrative that includes approaches, methods, limitations, results and conclusions. With each major chapter, a synopsis or abstract is included. The document also contains references that are listed in a bibliography. The appendices contain a

lexicon of abbreviations and general terms used in the report, a list of building numbers, and other more detailed scientific and technical information and overviews.

2.0 INTRODUCTION TO RADIOLOGICAL HAZARDS IN THE INDUSTRIAL SETTING

Synopsis *¾ Radiation may exist in a variety of industrial, occupational and environmental settings. Ionizing radiation can cause damage in biological systems, which may lead to cellular, tissue or organ changes and diseases. Some of the types of radiation include alpha particles (e.g. from ^{239}Pu and ^{237}Np), beta particles (e.g. from ^{3}H and ^{99}Tc), gamma rays (e.g. from uranium daughters) and neutrons (e.g. from alpha interactions with elements such as fluorine in UF_6). The energy of the radiation transferred to another material (e.g. air, biological tissues) can be measured. These measurements are called "dosimetry". For regulatory purposes, radiation doses are expressed as to "normalize" the relative risk of biological damage that the different types of radiation produce and to also express this over a number of years that a worker may have been exposed to a particular radiation. Thus, the unit "committed dose equivalent" is used for organ or tissue dose, reflecting the organ dose that may accumulate during the 50 years after an uptake and the unit "committed effective dose equivalent" is used to enable the summation of internal and external doses of similar biological risk.*

Biological effects of radiation are usually divided into 2 major categories. The effects that are predictable and are a function of dose are called "non-stochastic" or "deterministic" effects. These are usually seen with higher doses of radiation. Of greater interest in this assessment, are the lower dose effects that may or may not be observed, called "stochastic" effects - are those that may occur by chance. Stochastic effects (e.g. radiation induced cancers), when observed, are those resulting from lower doses received over longer periods of time.

2.1 Types of Radiation

Radiation may exist in a number of industrial, research and even environmental settings. Radiation is defined as the process by which energy is emitted or propagated through space as particles or waves. The term "ionizing" radiation is used when the energy of the particle or wave is sufficient to interact with matter in such a way as to remove electrons from atoms or break molecular bonds. The various types of waves and particles that might be encountered in an industrial setting, such as a gaseous diffusion plant are presented briefly.

The nucleus of an atom that has excess energy can release that energy through a process called "radioactive decay" - thus materials that emit particle and/or wave radiation are termed "radioactive". Nuclides (species of atoms characterized by the constituents of their nucleus, e.g., stable hydrogen and tritium are the same element, but different nuclides) that are radioactive are called radionuclides. Radionuclides of the same chemical element, but with different masses, are called "isotopes". For example, plutonium has several isotopes of varying masses, including ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu. The most common forms of radioactive decay are given below.

2.1.1 Alpha Decay

Radionuclides of many heavy elements (e.g. uranium, thorium, plutonium, and neptunium) decay by the emission of an "alpha particle". An alpha particle is the same as the nucleus of a helium atom, consisting of 2 protons and 2 neutrons bound together such that they behave as a single, unified particle. Because it is a fairly massive particle, in atomic terms, has an electronic charge of +2 and travels at a relatively low velocity, it readily interacts with normal matter producing a large number of ionizations over a very short distance before stopping. For example, in biological tissues an alpha particle from ^{239}Pu might only travel up to 100 µm, or one-tenth of a millimeter. Because alpha particles can cause a high density of ionizations, it can cause significant biological damage over this short range. However, unless alpha-emitting radionuclides can get inside the body through inhalation or ingestion, the hazardous effects of alpha radiation in the workplace are negligible, since they are unable to penetrate the outer dead layer of skin.

Examples of isotopes that emit an alpha particle include ^{235}U, ^{238}U, ^{239}Pu and ^{237}Np**.**

2.1.2 Beta Decay

Beta particles are high-speed electrons emitted from the nucleus of an unstable atom with usually less energy than alpha particles. The ejected electron is the same as any other electron, but is called a "beta" particle because it is emitted from the nucleus. Beta particles have a range of energies and may travel up to several meters in the air, but only several millimeters in biological tissues. Because beta particles have less charge and mass than alpha particles, there are fewer interactions (ionizations) with biological tissues. Thus beta particles when incorporated into biological systems (e.g. inhalation of a radionuclide) are generally considered less hazardous than alpha particles in many, but not all, practical situations. In the workplace, however, higher energy beta particles are able to penetrate the outer, dead layers of the skin, depositing their energy in living tissues. Since most of the vital organs of the body are deeper, they are unaffected by beta irradiation from external sources.

Examples of isotopes that emit a beta particle include ^{3}H (tritium), daughter products of the decay of uranium, and ^{99}Tc.

2.1.3 Gamma Ray Emissions

The emission of gamma rays to carry away excess energy from an unstable nucleus is often, but not always, accompanied simultaneously with the emission of particle radiation (e.g. alpha and beta particles). Gamma rays are similar to X-rays, but are a higher frequency – thus more energetic – form of electromagnetic radiation. The technical difference between gamma rays and X-rays is that the former are emitted from the nucleus of the atom while X-rays are emitted from the inner electron shells encircling the nucleus. Gamma rays can travel for some distance in air and are highly penetrating in biological systems – more so than alpha or beta particles. When gamma rays pass through biological tissues, ionizations and excitations can occur that may have some biological consequences. Because of their high degree of penetration, gamma rays can present an equivalent radiation hazard either external or internal to the body.

Examples of isotopes that emit a gamma ray include radionuclides resulting from the alpha decay of ^{238}U and ^{239}Np.

2.1.4 Neutrons

Neutrons are uncharged, highly penetrating particles that are one of the basic components of the nucleus of an atom. They have essentially the same atomic mass as a proton. Neutron emissions are usually produced from nuclear fission reactions. That is, when the nucleus is split in two. Some of the transuranium elements (those heavier than uranium) can undergo spontaneous fission and produce neutrons. Neutrons can also be released in a (α,n) reaction. This is a nuclear reaction where an alpha particle interacts with an element generating a second element and a neutron. Some examples are:

$$^{9}_{4}Be + ^{4}_{2}a \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

$$^{19}_{9}F + ^{4}_{2}a \rightarrow ^{22}_{11}C + ^{1}_{0}n$$

The later fluorine (F) reaction above is of interest due to the neutrons that may be produced from the interaction of alpha particles emitted from uranium with the fluorine in the various uranium compounds used at PGDP (e.g., uranium tetrafluoride (UF_4), and uranium hexafluoride (UF_6)).

Neutrons interact with matter in a different way than alpha, beta, or gamma radiation, and move quite freely through matter. So a radiation hazard may exist relatively far from the source. Neutrons can easily penetrate deep into the body, and depending on the energy of the neutrons, the hazards to biological systems can be more significant.

2.2 Measures of Radiation "Dose" in Biological Systems

Radiation of biological interest is ionizing radiation, and the "quantity" can be measured (in air) based on the number of ionizations produced. Such measurements are expressed in units of exposure called Roentgens (R). As ionizing radiation passes through biological tissue, it deposits energy. For this, the concept of "radiation absorbed dose" was developed and is the mean energy imparted by the ionizing radiation to a certain amount of mass. The conventional unit of absorbed dose is the rad and the International System of Units (SI) for radiation absorbed dose is the gray (Gy) (100 rad = 1 Gy = 1 Joule of energy per kilogram).

In biological systems it is important to quantify the relative radio-toxicity or damage that different types of radiation produce. In general, the higher the degree of ionization per unit length, or the rate of linear energy transfer (LET) of the radiation, the more effective it is in producing damage in a biological system. Radiobiologists have developed the concept of "relative biological effectiveness" or "RBE" to compare the differences in energy of a radiation type relative to the biological effect produced.

For radiation protection purposes, the concept of radiation absorbed dose is inadequate, because the RBE differs for different types of radiation. Thus the term “dose equivalent” was developed, which is the product of the radiation absorbed dose and a “quality factor” or QF (and any other modifying factors) to compare the relative effects to tissue due to various forms of ionizing

radiation. For example, it is known that alpha particles create much more damage than beta particles, so alpha particles are assigned a QF = 20 and beta particles are assigned a QF = 1. For most radiation protection and administrative functions, the doses are reported as "dose equivalents". The conventional unit is the rem and the SI unit is called the Sievert (Sv), (100 rem = 1 Sv). For organs or tissues, internal dose is integrated over the 50 years following an intake and is referred to as the “committed dose equivalent” (CDE) for that organ or tissue of interest. To allow the addition of external and internal dose the radiosensitivity of each organ or tissue must be taken into consideration. The "committed effective dose equivalent" (CEDE) incorporates a "tissue weighting factor" to compensate for differences in organ and tissue radiosensitivity.

For purposes of standard setting and radiation protection practices, annual limits are placed on the organ or tissue dose (CDE) and on the sum of any external and internal (CEDE) dose. Prior to 1992, the Department of Energy regulations required that internal doses be integrated only over the year of the intake. With the publication of the Radiological Control Manual, the Department of Energy transitioned to a 50 year CEDE.

2.3 Biological Effects of Radiation

It has been recognized for many decades that exposure to radiation involves some risk. From the early period of the development of nuclear industries, there have been recommendations (e.g., National Committee on Radiation Protection and Measurements in 1954 and the International Commission on Radiological Protection in 1958) that exposures should be kept as low as practical to minimize this risk. There are two general types of biological effects observed with exposure to radiation: deterministic and stochastic effects.

"Deterministic" effects are effects that occur as a function of dose. These effects are not considered to be probabilistic or to occur by some statistical chance. For this reason, they are often called "nonstochastic effects". These are effects that above a certain dose levels, or “threshold”, are almost certain to appear. These are seen with usually higher doses and occur promptly or soon after exposure. The severity of the effects observed above the "threshold" dose is directly related to the dose. An example of a non-stochastic effect of radiation is the formation of cataracts in the eye due to ultraviolet light, beta particles or low energy X-rays.

Of greater interest for the normal use of, and protection from radiation are the effects of lower doses. These effects occur randomly and are thus termed "stochastic" in their occurrence. The occurrence of stochastic effects is usually at longer periods following exposures. For example, in the watch dial painters exposed to radioactive radium during the early part of the twentieth century (1920's), cancers suspected as being caused by their exposures often did not occur until decades later in life [4].

Stochastic effects that appear in exposed individuals are called "somatic" effects. Those that occur in the progeny of the exposed individual are called "genetic" effects. The probability that a stochastic effect will occur is proportional to the dose received, but the severity of the effect, if it occurs, is not. For example, a cancer that might be caused by radiation might not be any more clinically severe than one that arose spontaneously. The most common stochastic effects of radiation observed in humans and experimental studies are cancers. While a specific radiation

cancer may not differ from a spontaneous, and presumed non-radiation induced cancer, different types of radiation exposures may lead to a statistical increase in the rates of certain types of cancers.

3.0 RADIOLOGICAL HAZARDS AT THE PADUCAH GASEOUS DIFFUSION PLANT (PGDP)

Synopsis *¾ The separation and enrichment of ^{235}U from natural uranium is done by the gaseous diffusion process. The potential hazard from natural uranium is both chemical and radiological. The incorporation of natural uranium into the body can result in nephrotoxicity (kidney toxicity) that may be observed within days of exposure. In addition to uranium there were other potentially more significant radiological hazards that existed at Paducah. The transuranic materials (^{239}Pu and ^{237}Np) were present in trace concentrations in some of the feed material. The potential concentration of this material within certain process equipment and potential worker exposures to this material was not fully appreciated, particularly during the first few years of plant operations. Recent (1990's) radiological surveys indicate elevated levels of TRUs in most of the process buildings as well as some non-process buildings. This suggests that efforts to control TRU contamination over the years were not effective. Additionally, there were some fission products (e.g., ^{99}Tc), thorium, and uranium progeny present. There were thus potential exposures to alpha, beta and gamma irradiation. The potential for neutron exposures seems low, but this has not been well documented. The TRUs, thorium-230, uranium progeny and fission products were concentrated during the process, and thus workers in certain areas and performing certain duties were at increased potential for radiation exposure. A large percentage of the plutonium, for example, was believed to have remained in the ash generated during the conversion of the UF_4 to UF_6. The potential for exposures also appeared to be increased during maintenance operations, system upgrades and incidents and accidents. There were also, for a limited time, recovery programs for ^{99}Tc and ^{237}Np, which presented additional potential for radiation exposures to the workers because of the concentrations of these materials. There may have been exposures to tritium (^{3}H) from metal components of weapons that were being recycled. Additionally, there were other areas where potential exposures to fission products, thorium, and uranium progeny may have occurred.*

3.1 Overview of the Separation of Uranium Isotopes by the Gaseous Diffusion Process

Natural uranium consists of several isotopes, the primary ones being ^{238}U, ^{234}U and ^{235}U. Uranium-235 has more favorable fission characteristics suitable for sustaining a nuclear reaction than natural uranium and is therefore better suited to be used as a nuclear fuel. However, the concentration of ^{235}U found in natural uranium is about 0.7 %. To be better useful as a nuclear fuel, the uranium must contain a higher percentage of ^{235}U (>3%). The process of increasing the ^{235}U content is referred to as "enrichment." The gaseous diffusion process has been the most utilized method for the production of materials with commercial concentrations of ^{235}U.

The separation of the isotopes of uranium by the gaseous diffusion process is based on the principal that these two isotopes have slightly different molecular masses or weights, and slightly different velocities at a given temperature. When introduced into a gaseous stream, the slightly lighter isotope will have a higher velocity than the heavier one. The lighter isotope will therefore

come in contact with the porous walls of the containment chamber more frequently and diffuse through resulting in a slight separation of the isotopes.

Since the average weight difference between the isotopes of uranium is very small, in order to achieve a significant separation, the gaseous mixture must go through multiple diffusion processes or stages called "cascades". For example, to enrich uranium from its original natural concentration of about 0.7% to about 4% ^{235}U requires about 1,200 diffusion stages.

The uranium must be converted into a gaseous stream to undergo the diffusion separation process. The most suitable gaseous compound was found to be uranium hexafluoride (UF_6). Uranium oxide (UO_3) is converted to UF_6 through a three step chemical process. Because UF_6 is a solid at room temperature, the diffusion cascades are operated at higher temperatures to maintain UF_6 as a gas. UF_6 is, however, highly reactive with water, common metals and lubricants and can be very chemically hazardous to humans. For this reason, the cascade must be as leak proof and as clean as possible.

The UF_6 feed material for the cascades came from a variety of sources. For example, at the PGDP, these sources included UF_6 from the Oak Ridge Gaseous Diffusion Plant (ORGDP) cascade tails, recycled UO_3 (yellowcake) from Hanford and Savannah River Project reactor tails, UO_3 processed from raw uranium, recycled PGDP cascade tails and uranium salvaged from various wastes and effluents which was converted to UO_3. Trace quantities of fission products and transuranic elements were introduced into PGDP via the reactor tails.

3.2 Site History of the PGDP

The Paducah Gaseous Diffusion Plant (PGDP) is located in Western Kentucky, about 10 miles west of the City of Paducah. The plant site occupies about 3,425 acres of which about 750 acres are within the security fence. The plant is in a rural area and some areas adjacent to the site are protected conservation, wildlife and recreation areas. From the start-up of production in 1953 to the present day, the primary function of the Paducah Gaseous Diffusion Plant has been to produce enriched uranium for use by commercial reactors or as feed material for other plants that further enrich the uranium.

The history of the site was presented in the Phase II report [2] but more of the radiological milestones are presented here and also in tabular form in Table 3.1. Construction of the plant began in 1951 through 1956. The first contractor for the plant was Union Carbide who operated it from startup until 1984. During the first phase of construction the gaseous diffusion cascade process (Bldgs. C-331, C-333), UF_6 feed plant (Bldgs. C-410/420), Purge and Product Withdrawal Building (Bldg. C-310), and the Surge and Waste Building (Bldg. C-315) were constructed. See Appendix C for more detail on the description of the buildings and processes discussed in this report.

The Cascade process in Bldgs. C-331 and C-333 began operation in September 1952 using UF_6 tails from the Oak Ridge Gaseous Diffusion Plant (ORGDP). In 1953, Building C-410, which contained an oxide conversion system, became operational. It was fed with recycled UO_3 from the Hanford Reactor. For the first four years, fresh feed material consisted of approximately

equal amounts of ORGDP UF_6 and recycled UO_3 from Hanford. In 1956, the new oxide conversion facility was opened in C-420, which was an annex on the west end C-410. This coincided with the processing of clean UO_3 that began on a small scale in that year. The upper cascade buildings, C-335, C-337, became operational in July 1954. Somewhere in this time frame, the decontamination building, C-400 was completed and began operation.

A uranium metals and hydrofluoric acid salvage operation was started up in 1957 in Building C-340 and was not completely shut down until the late 1970's, after which C-340 was used mainly for instructional purposes.

There were two cascade improvement/upgrade programs (CIP/CUP). The first of these ran from 1954 to 1962 while the second one was from 1973 to 1981. These were significant because of possible worker exposure to transuranics while the cascade systems were open. Other major events were the closing down of the feed plant operations from 1965 to 1969 and in 1971. The feed plant and the decontamination building were permanently shut down in the late 1970's.

The presence of the transuranium elements, neptunium and plutonium, in the cascade was confirmed by radiochemical analysis in 1957, but was recognized as early as 1953 [5]. In the early years of plant operations, neptunium was referred to as "trace". In 1958, a neptunium recovery program was implemented where it was extracted from the receiver ash and cylinder heels; locations where it was more concentrated.

Technetium is a fission daughter product and a program to recover this element was implemented beginning in 1960 and ending in 1963.

Based on interview reports it appears that there were incremental improvements in worker safety and personal protection programs during the 1980's that were accelerated following the publication of the "Tiger Team" Report in 1990 [15].

Union Carbide was the initial contractor at the site. Martin Marietta replaced Union Carbide in 1984. Martin Marietta merged with Lockheed to form Lockheed Martin in 1993. Congress established the United States Enrichment Corporation (USEC) as part of the Energy Policy Act of 1992. USEC was established as a government owned corporation to manage the uranium enrichment enterprise and prepare it for privatization. USEC commenced operations on July 1, 1993 and operated until July 28, 1998 when it was privatized through an initial public offering. The DOE awarded Bechtel Jacobs LLC the managing and integrating contract for environmental restoration in 1998. In May of 1998 USEC terminated Lockheed Martin as the managing and operating contractor and assumed responsibility for the gaseous diffusion operations at the PGDP.

The net effect of these many changes is that the areas of the PGDP that are leased by USEC are subject to regulation by the Occupational Safety and Health Administration and the Nuclear Regulatory Commission and the areas that are retained by the DOE under the stewardship of Bechtel Jacobs LLC remain regulated by the DOE.

Table 3.1. Overview of the PGDP chronology with emphasis on events that may have had some radiological consequences.

Date	Company	Event
Oct 1950	Union Carbide	Paducah Site selected
July 1952		Uranium received
Sept 1952		Cascade buildings C-331 and C-333 begin operation
1953		Aware that feed from recycled reactor fuel contains trace quantities of plutonium
Sept 1953		2 ash handler's urinalysis test positive for Pu
July 1954		Cascade buildings C-335 and C-337 begin operation
Aug 1954		First cascade improvement started, plant remains in operation
Aug 1956		C-420 feed plant online
Nov 1956		C-310 fire
Jan 1957		Begin producing U metal and UF_4 from depleted uranium
1957		Radiochemical analysis confirms presence of neptunium and plutonium (separate radiochemical analysis indicates entire cascade is contaminated with Np)
Nov 1958		Neptunium recovery started from receiver ash and cylinder heals
Apr 1960		Technetium recovery begins
June 1961		First cascade improvement completed
Sept 1961		MgF_2 traps installed to capture Np in effluents
Mar 1962		C-340 explosion and fire due to burnout of Mg bomb where uranium was released to the furnace
Mar 1962		Neptunium recovery ends
Dec 1962		C-337 Explosion and fire
Jan 1963		Technetium traps installed
June 1963		Technetium Recovery Ends
Apr 1968		Radiation overexposure to two maintenance workers*
Mar 1973		Second cascade improvement started
Oct 1973		No longer produces U metal, however still produces UF_4 as a by-product of HF recovery
Jan 1975		NRC and ERDA assume AEC
Mid 1970's		Tc removed as an environmental protection measure
May 1977		Feed plant ceases operation, receive feed as UF_6
Oct 1977		DOE assumes ERDA
Jan 1978		C-315 explosion and fire
Sept 1981		Second cascade improvement completed
Apr 1984	Martin Marietta	
June 1990		Tiger Team Assessment

Date	Company	Event
1992		USEC established
July 1993	Lockheed Martin	
July 1993	USEC (United States Enrichment Corporation)	Leases enrichment production facilities as operations and maintenance contractors
Nov 1996		NRC grants certificate of compliance to USEC
Apr 1998	Bechtel-Jacobs	DOE clean-up contractor
May 1999	USEC	Assumes direct operation of enrichment facilities

*Cited in the Phase II report, reference #2.

3.3 Plant Processes and Locations Where Potential Radiological Hazards Existed

There were several sources of radiation at PGDP that present the potential for worker exposures to alpha and beta particles, neutrons and gamma rays. These were derived from a variety of nuclides including uranium-234, uranium-235 and uranium-238, uranium progeny, transuranics (principally plutonium and neptunium) and fission products (technetium-99, etc.). Biological damage can result from either or both internal and external exposures. These are discussed in the context of plant operations in Appendix C. A detailed listing of worker occupations, plant locations and information relating to radiation exposures can be found in Appendix F.

From 1952 to approximately 1980, the major sites of potential exposure to nuclides were the buildings involved in the conversion of UO_3 powder to enriched UF_6 solid/gas, UF_4 and uranium metals recovery operations and the decontamination building. The feed and enrichment operations were located in Buildings C-410, C-420, C-331, C-333, C-335, C-337, C-310 and C-315, while UF_4 recovery and uranium recovery were done in C-340 (Figure 3.1). The decontamination operation was located in Building C-400 that also housed a number of other operations including the pulverizer and uranium, neptunium and technetium recovery. Localized sites within other buildings where exposure to radioactive materials could possibly have occurred included the compressor shop in C-720 and the cylinder transfer facility in C-360. Lesser exposures were possible at other sites including C-710, C-720 and C-746. During the 1973-1981 cascade improvement, a shop for reassembling and testing converters was located in C-409, the stabilization building.

The oxide conversion building, C-420 was where the UO_3 powder (clean or recycled) was received and converted into UF_4. From here it went to C-410, the feed plant, for conversion to UF_6. Finally, the UF_6 was processed through the cascade buildings, C-331, C-333, C-335 and C-337. Enriched UF_6 was withdrawn in C-310, the product withdrawal building, while depleted UF_6 was removed in C-315, the tails withdrawal building.

As mentioned above, the oxide was introduced into the system in C-420. The ore was run through two sets of fluidized beds, the first of which converted UO_3 (yellow powder) to UO_2 (black powder), while the second converted UO_2 to UF_4. The primary potential for radiation exposure to operators involved here were the inhalation of dust generated while unplugging the

converters or while cleaning the building air filtering system (bag house). The maintenance mechanics had a potential for exposure while working on the equipment.

In the early days before C-420 was built, a feed plant was established in C-410 for converting UO_3 to UF_4. According to the phase II report, this operation was "hazardous and subject to frequent breakdowns" [2]. In about 1956, it was shut down. Information on this part and time of the plant operations is meager.

The next stage of the enrichment operation was to convert solid UF_4 to gaseous UF_6. This was done in fluoridation towers located in C-410. The operation consisted of introducing UF_4 at the top of the tower while fluorine gas was introduced from below. The resulting UF_6 gas/liquid was removed in large cylinders while the solid waste products were collected in ash receivers at the bottom. The radiological issues here were potential beta and gamma radiation exposures from transuranics, fission products and accumulated uranium daughters, which were concentrated by the process in the ash at the bottom of the fluoridation towers. In addition to any external radiation sources, there was also the possible inhalation of dust while cleaning plugged equipment, change out of the ash receivers, ingestion during maintenance work and cleaning the building air filters. The potential for radiation exposure was particularly increased for work around and with the ash receivers.

From the Feed Plant, the UF_6 gas was introduced into the cascades that were located in Buildings C-331, C-333, C-335 and C-337. Potentials for exposures were greater when it was necessary to perform maintenance work on the compressors, to unplug or replace control valves or to clean the building air filters. The exception to the above was during the cascade upgrade program of 1973-1982 when the system was opened up to modify the converters and large amounts of UF_6 gas were released.

Another work site for potentially increased radiation exposures was the Decontamination Building, C-400. This was primarily because the following operations were performed there, converter disassembly, pulverization of waste UF_4 and recycled UO_3 containing transuranics, cylinder heel cleaning, the spray booth operation and neptunium and technetium recovery. There were hazards associated with cleaning the building air filtering system (baghouses).

Two buildings with reduced potential for TRU exposures were the Product Withdrawal Building, C-310, and the Tails Withdrawal Building, C-315. An interesting practice that occurred here was that of attaching a valve called a pigtail, to the gas cylinder that was to be filled. Usually when this operation was performed, there would be a small release (called a puff) of UF_6 gas into the immediate environment. Other potential exposures in these buildings included operators who moved a gas cylinder before it had been disconnected from the building gas lines (at least twice) which resulted in breakage of the pigtail, and an accident where a piece of equipment (a scale) fell on the pigtail and broke it off [16].

Another building which had an increased potential for radiation exposure was Building C-340, the metals production building. Reacting depleted UF_6 tails from the cascade operation with hydrogen gas produced depleted uranium. HF was produced as a byproduct of this reaction, which was then reused in the feed plant. UF_4 was either stored or used to produce uranium metal.

The potential radiation exposure resulted from the need to unplug stoppages in the conversion towers and various operations involved in manufacturing and cleaning uranium "derbies". A "derby" was the molded uranium metal that was made from the UF_4 and magnesium. Finally, there were the usual potential radiation exposures involved in cleaning the building air filtering system and maintaining the equipment.

Further technical details on plant processes and activities within specific buildings are found in Appendix C.

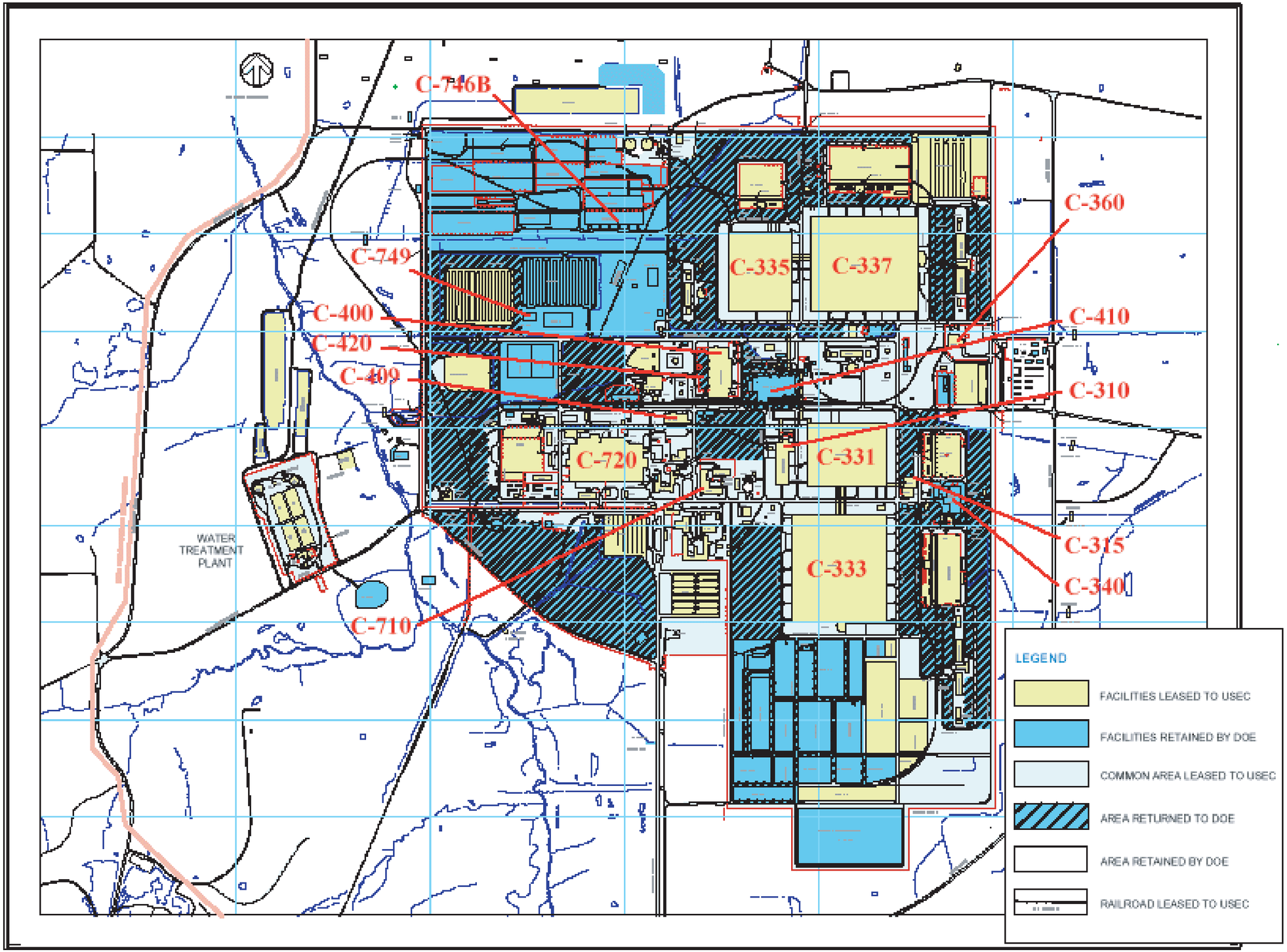

Figure 3.1. Schematic drawing of approximate locations of PGDP buildings of interest in this report. See also Appendix C for a detailed description of the facilities and processes.

3.4 Transuranic Elements - Neptunium and Plutonium

The transuranic elements (TRU) of interest in this assessment are ^{237}Np and ^{239}Pu. The transuranics were present in some of the feed materials as contaminants in trace concentrations. This included the recycled uranium that came from plutonium production reactors at Hanford and Savannah River via the Feed Materials Production Center (FMPC) at Fernald, Ohio. The use of this feed material ("reactor tails") began in July 1953 [17] and it was known at the time that this would introduce what was felt to be negligible or trace quantities of transuranics and fission products into the gaseous diffusion system.

Neptunium-237 has a radioactive half-life of about 2.14 million years with a specific activity of $7.06E^{-4}$ Ci/g. Because it has a greater specific activity than uranium, it is about 2,000 times more radioactive per unit mass than depleted uranium. For this reason, the presence of ^{237}Np in the feed material and its concentration during the enrichment process presented a potential for increased worker radiation exposure.

Plutonium-239 has a radioactive half-life of about 24,400 years, and is thus much more radioactive per unit mass ($6.2E^{-2}$ Ci/g) than ^{237}Np. Both ^{239}Pu and ^{237}Np are alpha emitting isotopes, thus they must be incorporated into the body to promote radiation damage. The primary pathways of incorporation would be by ingestion or more importantly by inhalation. The longer-term biological consequence of exposure to TRUs or any other internally incorporated material depends upon where it is deposited and retained in the body. After an inhalation exposure, the materials may be absorbed and translocated to other tissues. This will depend on the solubility and size of the inhaled particles.

3.4.1 Sources and Amounts of Transuranics at the PGDP

The Team summarized the amounts and dates of introduction of TRUs at the plant, based on available documentation. The following table (Table 3.2) contains a list of the total amounts of ^{237}Np and ^{239}Pu reported as being received at PGDP along with the time of receipt and the document from which the information was extracted. These are preliminary estimates that will be updated when the Mass Balance Team produces its report.

Table 3.2. The amounts of ^{237}Np and ^{239}Pu reported at the PGDP, years represented in the report, year of the report, and the bibliographic reference. The list is sorted by the year of the report that contained the information.

Radionuclide	Amount (kg)	Date	Year of Reference	Reference #
Np-237	2.847	2/57 - 2/64	1966	7
	11.386	12/56 - 6/64	1966	8
	13.084	12/56 - 12/70	1972	9
	13.548	6/53 - 11/73	1974	10
	18.4	FY53 - FY76	1984	11
	18.0	FY53 - FY84	1986	12
	18.0	6/53 - FY77	1987	13

Radionuclide	Amount (kg)	Date	Year of Reference	Reference #
Pu-239	0.189	2/57 - 2/64	1966	7
	0.189	12/56 - 6/64	1966	8
	0.2257	12/56 - 12/70	1972	9
	0.271	12/53 - 11/73	1974	10
	0.328	FY53 - FY76	1984	11
	0.33	FY53 - FY84	1986	12
	0.33	6/63 - FY77	1987	13

The above table was based on available records, estimations, and assumptions. From these documents the best estimate for the amount of ^{237}Np received at PDGP is about 18.4 kg. The best estimate for the amount of ^{239}Pu is about 330 grams. These figures are similar to those reported by R.C. Baker [25] where he estimated that about 100,000 tons of uranium was processed and this contained 660 kg (about 11,000 curies) of ^{99}Tc, 18 kg (12 curies) of ^{237}Np and 330 grams (20 Curies) of ^{239}Pu. Additionally, according to available documentation the PGDP feeds were not analyzed for neptunium and plutonium from 1953 to 1957 so that their contribution during this time frame has been estimated. As part of the Mass Balance initiative, the PGDP is reporting that 22.866 kg of ^{237}Np and 300 gm of ^{239}Pu were received between 1953 and 1988.

3.4.2 Specifications of the Transuranics at the PGDP

Specifications on quantities of transuranics in reactor return uranium were devised to assure that radiological limits and handling practices for uranium would automatically satisfy similar standards for transuranics [26]. The limits also serve to reduce the cost of removal of these contaminants. As a consequence of detection improvement over time, these limits have undergone change from the beginning of plant operation until current day standards.

As early as 1953, documents describe the maximum "acceptable" concentration of plutonium in the feed material to be 10 parts per billion (ppb) uranium [17]. The earliest specification for acceptable concentrations of neptunium in feed material that the Team found was in a document dated 1966 [18]. Later it was specified [18] that alpha activity from reactor fuel elements could not exceed 150 dpm/g U. This means that the amount of activity due to alpha emissions could not exceed 150 disintegrations (alpha particles) per minute (dpm) per gram of uranium. Since uranium undergoes alpha decay, limiting its activity controls the level of radioactivity received at the plant for processing. This document also specified that the alpha activity from plutonium would not exceed 136 dpm/g U that could be represented by 0.0004 ppb U basis for ^{238}Pu, 1 ppb U basis ^{239}Pu or 0.3 ppb U basis for ^{240}Pu. Since each isotope has its own specific activity the amount of each isotope that can be present without exceeding the limit varies.

In 1975 [23] the feed specification was not to exceed 1500 dpm/g U for neptunium and plutonium as established in 1967. As this shows, the limits changed from 1966 to 1967 by an order of magnitude and the ^{237}Np limit became 1 ppm U basis. By 1986 the limit for RT (reactor tails) material contained plutonium in quantities equal to or less than 10 ppb U basis (10 ppb of 100,000 tons U is 1000 g) [24]. These levels changed by orders of magnitude over the 1967 specifications.

By 1989 the specifications for plutonium and neptunium combined decreased to 200 dpm/g U. The specific activity for ^{239}Pu is $1.4E^{11}$ dpm/g, which limited the concentration of plutonium to 1.4 ppb U basis. Likewise, the specific activity for ^{237}Np ($1.6E^{9}$ dpm/g) limited the concentration of neptunium to 125 ppb U basis. The Mass Balance Team in their report will discuss a more thorough review of the feed material specifications.

3.4.3 Activities and Concentrations of Transuranics

Because neptunium and plutonium move through the cascade process at different rates from It was common in the plant records to express plutonium activity as a percentage of neptunium activity. One of the 1966 documents [18] assumed plutonium alpha activity did not exceed 1% of the neptunium alpha activity for the period from 1953 to 1966. This assumption was based on measurements of neptunium in the cascade process and extrapolating the plutonium percentage based on the chemical properties of the two radioisotopes in the diffusion process and the assumption of the relative amounts present in the feed material. Another document issued within days of the first [19] assumed plutonium alpha activity was less than 1% of neptunium alpha activity. Additionally, this document estimated that the highest concentration of neptunium received was 100 dpm/g U.

In 1984 [22] it was assumed plutonium alpha activity was less than 0.2% of neptunium alpha activity based on supposed neptunium and plutonium ratio measurements that were taken. However, the number or methods of measurements were not disclosed. This document reports the highest average concentration for neptunium to be 0.24 ppm U basis before fiscal year 1967. The highest average concentration for plutonium was reported as 4.5 ppb U basis in ERT (enriched reactor tails) stream with no specified time period. Prior to 1967 it was speculated that due to ratios and the quantity of feed, the upper amount of Pu entering the plant was 4 ppb U basis as determined by unspecified measurements that were reportedly biased high. Plutonium concentrations in this range indicate a possible violation of the specification indicated in a 1966 document [19].

3.4.4 Plant Processes and Locations That Involved Transuranics

As briefly described earlier in this report, the first stage in the enrichment of uranium ores at PGDP was the conversion of UO_3 to UF_4. Since this was a solid-to-solid conversion, the concentration of transuranics and fission products remained the same as that of the starter material. The next step was fluorination of UF_4 to UF_6. This was a solid to gaseous conversion that resulted in the formation of insoluble solids and gaseous fluoride compounds. Much of the transuranic contamination remained behind in the ash receivers (solid waste products). The remainder was probably converted to analogues of UF_6, namely, NpF_6 and PuF_6. The above operations took place in the feed plant (building C-410). Figure 3.2 shows the feed material (UF_6) being removed via transfer cylinders while the solid wastes were taken out in ash receivers.

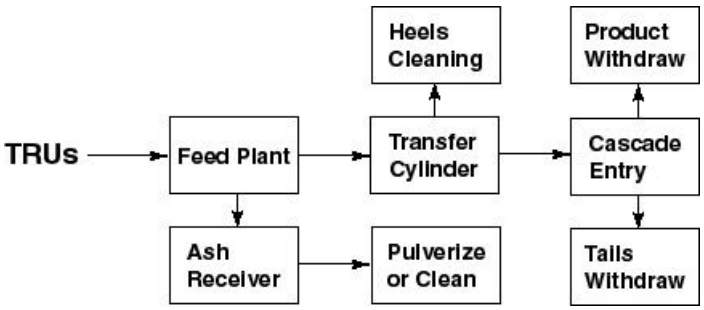

Figure 3.2. Flow Chart of Transuranics Movement at PGDP.

NpF_6 and PuF_6 had a high affinity for the walls of the stainless steel cylinders, which were used for transporting the UF_6 to the entry points of the cascade (buildings C-331, C-333, C-335, C-337). A substantial amount of the remaining neptunium plated out at this point and remained as part of the cylinder "heels". This "heel" material was an insoluble residue that formed with time in the UF_6 cylinders. The remainder was transferred back into the cascades.

Beginning in about 1957, measurements were made of the NpF_6 content of the cascade feed material [22]. The percent of alpha activity attributable to neptunium ranged from about 10 to 40% with most of the values being on the lower end of the range. Using a value of 25%, it was estimated that 4.6 kg of neptunium entered the cascade. This is twice as high as the value of 2.3 kg given by a 1990 document [26]. Assuming most of the uranium starter material was converted to UF_6 and accepting the high value of 40% in the cascade, this would mean a concentration of 79.2 ppm U of neptunium and 1.6 ppb U of plutonium that is lower than that of the starter material. Such values are believed to be conservative since neptunium and plutonium are highly reactive with the nickel lining of the cascade piping and diffusion barriers and a large percentage is believed to have plated out as reduced neptunium and plutonium fluorides shortly after entering the system (at the feed points) [26]. From this point, there is an equilibrium which results in small quantities of neptunium (and possibly plutonium) being released back into the UF_6 gas and finally going out in the product withdrawal cylinders.

It is believed that a large percentage of the plutonium remained behind in the ash receivers and cylinder heels as a result of processing that took place in the Feed Plant (410/420). Available references reported a value of approximately 0.1 g of plutonium to have entered the cascades [26]. In theory, most of the neptunium would be in the form of reduced fluorides adhering to the surface of the pipes and diffusion barriers, and not as NpF_6. Indeed, neptunium contamination of the process equipment was first reported after a pipe that was being modified in the weld shop was found to have “unusually high” fixed and removable alpha activity that was later determined to be Np-237 [27].

After the neptunium (and plutonium) had entered the cascade, it was available to create potential worker radiation exposures via the following:

1. Routine maintenance and repair of cascade components.
2. Cascade improvement programs.

3. Melting of salvaged nickel.
4. Legacy contamination.

Additionally, surface wipe data from 1990-1991 radiological surveys [7,8] indicating relatively high values of transuranics throughout the process buildings suggests another source of transuranic exposure. The IT report [8] gave values of 85.9%, 11.0% and 3.3% for uranium, neptunium and plutonium respectively in building C-333, one of the cascade buildings. If the assumption is made that the units in the IT report are percentages of total alpha activity [8], then conversion to ppb values would indicate that the concentrations were about 60,400 ppb U of neptunium and about 260 ppb U of plutonium. These values for plutonium would be very high relative to the specifications for the feed material.

UF_6 was withdrawn from the cascades in Building C-310, product withdrawal, and C-315 tails withdrawal. Based on process chemistry, neptunium and plutonium concentrations would not be increased in the product and tails withdrawal. Again, identified wipe data with elevated TRU levels confound this conclusion. Nonetheless, it is expected that the potential exposure to workers in this area was less than some other areas. Depleted UF_6 from building C-315 was used as a source of depleted uranium, which was produced in Building C-340.

Transuranics left the feed plant via transfer cylinders and ash receivers. A small quantity appeared to have also been captured by the air filtering systems, so called "baghouses". This system was designed to capture radioactive materials in the building air. It was estimated [26] that 20% of the introduced neptunium ends up in the ash receiver, 62.5% or more goes to the cylinder heels and 5% is collected in the baghouse filters.

The cylinder wash was added to waste solutions from the spray booths. Historically, two methods were used to harvest uranium from the washings. The first was a liquid chemical method where the end product was uranium trioxide, which was presumably sent to the pulverizer for conditioning before being recycled through the feed plant. The second method involved chemically reacting the washings so that a sludge or cake was formed which contained the uranium (and by inference, the transuranics) and a raffinate solution. The sludge, which contained most of the uranium and transuranics, was shoveled into barrels and stored. Because of the higher external radiation doses due to the presence of increased concentrations of uranium daughter products, worker exposure to the sludge was sometimes restricted.

The baghouse filters were periodically changed and cleaned. For this, the workers would open the system and beat on the bags with sticks, which would create considerable dust and airborne materials. It appears that wearing a respirator was required for this activity. The dust from the baghouse filters was collected and emptied into barrels that were then placed in storage. There was a potential for some exposure to the dusts during the entire procedure.

It was estimated [26] that 3.7 kg of neptunium left the feed plant via the ash receivers. The composition of the ash varied depending on how efficient the fluorination process was. If conversion was poor, most of the ash consisted of unreacted UF_4 with lower concentrations of transuranic contamination. On the other hand, if conversion was good, then the ash was made up of reduced uranium fluoride products with higher levels of transuranic contamination.

The relatively pure material was sent over to the pulverizer in C-400 and reconditioned, before being reprocessed in the feed plant. The impure material was put into storage for six to eight months to allow the short-lived uranium daughter products to decay. After this, information indicates it was sent to the pulverizer for reconditioning after which it was shipped to Fernald for uranium reclamation.

There was one documented case where a batch of material was sent to Fernald in June of 1980 that was found to have particularly high levels of plutonium. According to one document [8], the plutonium levels ranged from 67 to 7,757 ppb U. Corroborating this was the Baker report [25] that suggested that concentrations of 80 to 1,000 ppb U were found in the ash receiver contents.

Smear sample data were reported in the early 1990's [7] from various locations within buildings C-310, C-331, C-333, C-335, C-337, C-360, C-400, C409, C-410, C-710, C-720, and C-746Q and within locations where TRU may have accumulated. Forty-nine of the 95 samples are reported to exceed the action level for TRU.

Based on the above observations, it appears that the workers that had the greatest potential for radiation exposures to the transuranics were:

- Chemical operators
- Feed plant operators
- Maintenance mechanics

3.5 Specific Recovery Operations for Technetium and Neptunium

3.5.1 Technetium Recovery Operation

Technetium-99 is the primary fission product of concern at the PGDP. It has a half-life of about 213,000 years and is a low energy beta emitter. Externally the beta particle is effectively stopped at the outer layers of the skin. The phase II report [2] noted "Although technetium was not a significant radiological hazard during most PGDP operation and maintenance activities, it presented a more significant hazard when concentrated in recovery processes in C-400" [l].

The technetium recovery operation was initially located in Building C-710 and was moved to Building C-400 sometime after 1959. From information supplied by the workers [3,28], the operation was located in an area near the center of the building (C-400) close by the spray booth and behind the compressor test area.

Although the technetium (and neptunium) recovery systems were supposed to be leak proof and made of unbreakable plastic, this does not seem to have been the actual case. Both the Phase II report and the workers [29] mentioned that parts of the apparatus were made of glass that sometimes broke. One worker mentioned mopping up "one million dollars worth of technetium," which had been spilled [30].

The recovery operations were only run sporadically until about 1975. The separation equipment

was then left in place until about 1980 when they were dismantled. The workers who did the dismantling were not told that the equipment was radioactively contaminated and hence did not exercise special safety precautions [29]. There was one incident where a technician in the analytical chemistry lab stated to have been "covered with technetium" [31].

Subsequent to the termination of the original technetium recovery process, other, apparently safer systems were set up at various locations to trap technetium so that it wouldn't escape into the system or the environment. Technetium and neptunium were recovered on a small scale from these systems [2].

3.5.2 Neptunium Recovery Operation

The neptunium recovery program preceded the technetium recovery program. After an initial development period in Building C-710, the neptunium recovery was moved to Building C-400. There were three cubicles in the back of the C-400 building. The one in the very back corner was used for mercury recovery, the next room was used for storage associated with the neptunium recovery operation and the third was the "trace" or neptunium recovery room.

The "trace" room was a little bigger than a normal sized room. It was built in such a way that an explosion would dissipate upwards, thereby minimizing damage to adjacent areas. Along one side was a series of four columns filled with an ion exchange resin (rosin) with containers that wouldn't let the resin fall through while allowing the flow of liquid. Above the columns were racks where 5-gallon carboys were placed. Mixed solutions would be placed on the racks and drained through the columns. The neptunium would accumulate in the columns after which a solution would be run through the column that neutralized it and the neptunium would be drained off. Once again, some components would break, potentially exposing the workers to radioactive materials. When the systems were later dismantled, some workers indicated that they were not informed that the components could contain radioactive contamination. The resulting product was sufficiently concentrated to be useable as a starter material for further purification, likely done at Oak Ridge.

Because the workers were handling more concentrated forms of neptunium, this operation had higher potential for internal radiation exposures.

3.6 Processes That May Have Produced Exposures to Neutrons

There is one primary potential source of neutrons present at the Paducah facility, excluding those that might be produced in a criticality incident. The source is from neutrons resulting from an (α, n) reaction with fluorine compounds. This could occur in the fluorination towers where the maximum amount of fluorine would be available for this reaction. Because of the size of the towers, the production of neutrons would be expected to be small. Neutrons could also be produced in the storage cylinders that contained either depleted UF_6 (tails) or enriched UF_6 (product). While there were badges issued for neutrons, there were few documents or reports that discussed or presented any radiological issues relative to neutrons.

3.7 Processes That May Have Produced Exposures to Tritium

Tritium is an isotope of the element hydrogen. It is about 3 times heavier, than normal hydrogen. Tritium has a half-life of 12.3 years and emits very low energy beta particles. It is normally present in the environment in extremely small amounts compared to normal hydrogen. Tritium poses essentially no external hazard since the beta particles released via the radioactive decay process cannot penetrate the outer layer of skin. However, tritium can be incorporated into the body through respiration, ingestion, and absorption through the skin. Once inside the body, tritium can pose a greater biological hazard; however, a relatively large amount would have to be taken in to result in doses that would be of concern.

Tritium has certain characteristics that present unique challenges for dosimetry. For example, in gaseous form, tritium can diffuse through almost any type of container, including those made of steel, aluminum and plastics. In oxide form (HTO), commonly used survey instruments cannot detect tritium. However, uptake of tritium can be easily monitored through bioassay of urine. The presence of tritium can be detected in the urine within 24 hours post-exposure and can be followed for several months. The so-called biological half-life of tritium (that is, the time for one-half the absorbed activity to leave the body) varies from 10 days to as long as 3 months depending upon how the tritium is metabolized.

The source of information on possible tritium exposures at the PGDP continues to come from the media, and not from documents acquired by the Team. For example, an article in the Louisville Courier-Journal dated Oct. 8, 1999 reported that a former Paducah worker was suspected of having a body burden of tritium. The article further states that the "United States Enrichment Corp. said yesterday it was testing a handful of employees at the Paducah Gaseous Diffusion Plant for exposure to tritium…" The article further states that tritium is not used in any processes at the plant and cannot account for the tritium in this worker.

A subsequent article in the Washington Post (Mar.14, 2000) discusses the possibility that the plant may have been involved with "weapons dismantlement" and that personnel could "conceivably encounter highly enriched uranium or plutonium (or even tritium) without knowing it". The Phase II Report does, however, state, "until 1985 disassembly of weapons components and recovery of metals were performed at PGDP"[2].

The types of components and the surveys performed on any components prior to shipment to the PGDP is classified, and such information was unavailable to the Team. Because of the nature of tritium – particularly its ability to diffuse into and through various types of materials – exposure to tritium contaminated weapon components may have been possible; however, the degree of exposure to tritium would probably be small. The Team found no record to date of a bioassay program for tritium. Without such data no true estimate of tritium exposure can be determined.

Thus no conclusions, based on factual data, can be drawn relative to the claim that workers at the PGDF were exposed to tritium. However, as stated above, the presence of tritium, probably in small amounts, was indeed possible. The doses delivered to the workers, if small amounts of tritium were present, likely would be extremely small.

3.8 Incidents and Accidents

Incidents and accidents deserve some attention because often in industrial settings exposures occur as a result of non-routine incidents and accidents. It is also evident that at least some, if not many, of the higher exposures that were found in the records can be tracked to some incident or accident. Many of the incidents and accidents were presented in the Phase II report [2] that noted that from the beginning of plant operations to the early 1990's, there were many releases, potential exposures, some accidents, and operational problems. Some of these incidents, such as small releases of UF_6 ("puffs") were apparently quite common. The phase II report [2] identified approximately 50 UF_6 releases, each releasing in excess of 10 pounds of uranium. The report also identified "at least 15 events…that each released a minimum of 100 pounds of uranium". Smaller "materials releases" were commonplace occurrences, especially in the early years of plant operations.

Several of the major accidents were well known including a major fire in Building C-310 in 1956, explosions and fires in Buildings C-340 and C-337 in 1962 and C-315 in 1978. With at least one of these fires, there was the possibility for exposure to fire fighting personnel who responded from the surrounding communities. There were "events" in 1960 and 1962, reported in the Phase II report, indicating releases of about 6,800 and 3,400 pounds of uranium, respectively. It was not clear if the doses that may have been received by many workers as a result of these accidents were measured, and if so, whether they were recorded in the database.

Of additional interest with regard to dose estimation is the practice reported by some workers of collecting urine samples within 30 minutes of an accident or incident [33]. If there were intakes of uranium, it may not be in the urine within 30 minutes. If subsequent samples were not taken, the intakes from these exposures may not have been identified. Some workers recollected that the follow-up samples were done if the initial "special sample" exceeded the plant action guide level.

4.0 HISTORY OF THE HEALTH PHYSICS PROGRAM AT THE PADUCAH GASEOUS DIFFUSION PLANT (PGDP)

Synopsis *¾ There were radiological standards in place during the entire history of the PGDP. These standards did change with time. As noted in the Phase II report, the working philosophy was to keep the worker exposures within the regulatory limits, rather than to keep the exposures as low as reasonably achievable (ALARA). Additionally the report noted that the enforcement of safety rules and implementation of procedures was the responsibility of the line supervisors.*

The detection of external doses was accomplished throughout the early plant history with film badges and after the 1980's thermoluminescent dosimeters (TLDs). It was apparent that when workers exceeded or approached their limits for the month or quarter, for example, they were transferred to locations where their exposures would be less, so as not to exceed the yearly regulatory limit. To assess the uptake of uranium, a bioassay program was conducted to determine concentrations of uranium in the urine. Higher samples resulted in recalls and sometimes workers were reassigned to another department or location to reduce their radiation exposure.

When it became apparent in the late 1950's that there were potential exposures to TRUs, some workers were sent for whole body counts and later a mobile whole body counter was used on site to assess total body concentrations of neptunium. Detectable levels of TRUs in workers were not reported, but there were some serious limitations of the techniques and equipment used.

There were never any routine bioassays for TRUs, instead it was assumed controlling uranium exposures could control exposures to transuranic materials. The content of plutonium and neptunium in wipe and air filter samples was, however, routinely reported in the health physics documentation for many years.

4.1 Historical Radiation Standards in Use at the PGDP

The exposure limits according to NBS Handbook 69 published in 1959 are as follows: 1) The maximum permissible dose (MPD) for penetrating radiation to the whole body was 5(N-18) rem, where N is the age of the person, and the dose in any 13 consecutive weeks shall not exceed 3 rem. An older person may receive a dose of 12 rem in a single year provided that his 5(N-18) limit was not exceeded (i.e. his average yearly dose does not exceed 5 rem/yr). 2) The MPD for non-penetrating radiation dose to the skin was 10(N-18) rem, and the dose in any 13 consecutive weeks shall not exceed 6 rem. For the hands, forearms, feet and ankles the MPD = 75 rem/year and shall not exceed 25 rem in any 13 consecutive weeks. 3) The maximum permissible concentration (MPC) value for air was set to conform to the above stated limits when applied to the most restrictive case (an 18 year-old). The MPCs for ^{237}Np, ^{239}Pu, ^{99}Tc, ^{235}U and natural uranium are listed in the following table for soluble and insoluble cases. These limits are the lowest limits and are based upon the most critical organs for each nuclide. The maximum permissible body burden (q) is also listed in the following table.

Table 4.1. NBS Handbook 69 – Maximum permissible values for occupational exposure in 1959.

Nuclide	Solubility	qmC	40 hours/week
			MPC_{air} mCi/cm^3
^{99}Tc	Insoluble		$1E^{-5}$
^{99}Tc	Soluble	200	$4E^{-5}$
^{239}Pu	Insoluble		$4E^{-11}$
^{239}Pu	Soluble	0.04	$2E^{-12}$
^{237}Np	Insoluble		$1E^{-10}$
^{237}Np	Soluble	0.06	$4E^{-12}$
^{235}U	Insoluble		$1E^{-10}$
^{235}U	Soluble	0.03	$5E^{-10}$
Natural U	Insoluble		$6E^{-11}$
Natural U	Soluble	0.005	$7E^{-11}$

Furthermore, the dose to persons in the neighborhood of controlled areas was not permitted to be more that 1/10 the MPCs. Their maximum permissible body burden is likewise 1/10 that listed in the above table. Their dose shall not exceed 0.5 rem/year.

The AEC and ERDA limits reflected the limits from NBS Handbook 69 for external exposure. The internal limits in NBS Handbook 69 are listed as maximum permissible concentrations (MPCs) in air and water, which were set by maintaining the 5 rem/year limit to the most critical internal organ for the nuclide of interest. The AEC/ERDA Manuals do not list MPCs, but do list the internal dose commitment limits.

The limits according to AEC Manual Chapter 0524 and ERDA Manual Chapter 0524 are listed below with modern limits for DOE facilities from 10 CFR 835. The limits remained constant from 1958 to 1968. The changes in 1968 are to the bone dose and whole body dose from an internal exposure. The bone dose is specified as an actual limit for the first time. The whole body dose was expressed as a 50-year accumulated dose instead of a yearly dose. In 1975 further changes were made. The internal dose to the thyroid was no longer specified. The dose to other organs was not specified. Also, the whole body dose from external or internal sources reverts to a specified yearly dose instead of the accumulated dose. Under the accumulated dose limit it was permissible to receive up to 12 rem in one year, as long as the accumulated dose limit was not exceeded. In 1975 and 1977, it was still permissible to get 12 rem in one year, but only under special circumstances. In 1977 the dose limits to other organs was reinstated. Furthermore, the dose to extremities was broken down into a limit for forearms and a limit for hands and feet. The dose limit to forearms was lower than previous specifications would allow. In 1988 the dose limits change once again. The quarterly dose was no longer specified. The external dose limit to the skin and extremities were set at 50 rem/year. The internal dose was expressed as a sum of the external exposure and the committed dose equivalent to any organ or tissue, with a particular limit specification of 15 rem/year to the lens of the eye.

In 1992, a change was made to how internal dose was recorded. Up to this point, internal doses were integrated over 1 year, the year of the intake, and any subsequent years. With the publication of the Department of Energy's Radiological Control Manual in 1992, internal doses were to be integrated over the 50 years following the intake.

Table 4.2. Dose limits. From 1958 – 1968 comes from AEC Manuals. 1975 and 1977 comes from ERDA Manuals. 1988-1999 comes from DOE Order 5480.11 and 10 CFR 835.

	External Dose (rem)			**Internal Dose (rem)**			
Year	Whole Body	Skin	Extremities	Whole Body	Thyroid	Bone	Other
1958	Accumulated 5(N-18)	2 times whole body	75/year		"not more than 1/4 of the 15 rem maximum permissible yearly dose shall be taken in 1/4 of a year"		
1963	Accumulated 5(N-18) 3/ qtr.	30/year 10/qtr.	75/year 25/qtr.	5/year 3/qtr.	30/year 10/qtr.	= 0.1 µg of Ra^{226} or biological equivalent	15/year 5/qtr.
1968	Accumulated 5(N-18) 3/ qtr.	30/year 10/qtr.	75/year 25/ qtr.	Accumulated 5(N-18) 3/qtr.	30/year 10/qtr.	30/year 10/qtr.	15/year 5/year
1975	5/year 3/ qtr.*	15/year 5/qtr.	75/year 25/qtr	5/year 3/qtr.		30/year 10/qtr.	
1977	5/year 3/ qtr.	15/year 5/qtr.	Forearms: 30/year 10/qtr. Hand & Feet 75/year 25/qtr.	5/year 3/qtr.		30/year 10/qtr.	15/year 5/qtr.
1988-1999	5/year**	50/year		Sum of the deep external exposure and the weighted committed dose equivalent to any organ or tissue = 50/year (lens of the eye = 15/year)			

*The AEC Manual also states "in special cases with the approval of the Director, Division of Safety, Standards and Compliance, a worker may exceed 5 rem/year provided his/her average exposure per year since age 18 will not exceed 5 rem per year."
**This limit is actually the sum of the external dose and the committed effective dose equivalent from all internal exposures in the current year.

The radiation limits employed with time, the references for these methods, the location, monitoring methods, and documented exposures are summarized in Appendix D. Exposure ranges to more specific worker groups may be found later in this document.

There is documentation indicating that throughout most of the plant history these radiation standards were being used. For example, in a 1961 report [34] it indicates that radiation exposure limits were taken from the National Committee on Radiation Protection (NCRP), AEC Manual Chapter 0524, NBS Handbook 52, and NBS Handbook 69. A monograph titled "Selected Material on Radiation Protection Criteria and Standards: Their Basis and Use" was published in May 1960 [35]. This document contains an Appendix titled "Application of Radiation Protection Standards at Atomic Energy Facilities Operated by Union Carbide Nuclear

Company" where it is stated that the "permissible radiation exposure limits used are those established by the National Committee on Radiation Protection as given primarily in NBS Handbooks 59 for external exposure and 69 for internal exposure". An interview with a health physics technician that worked at Paducah from 1953 to 1985 states “we had radiation standards from AEC and all back from day one”. This indicates that the Paducah Gaseous Diffusion Plant Health Physics personnel did have available to them the current radiation protection standards at that time. In the 1988, *DOE Health Physics Manual of Good Practices for Uranium Facilities* it is indicated that the limits were taken from ANSI and NCRP [36]. Furthermore, plant documents [37] contained copies of AEC 0524 dated 1958, 1963, and 1968 and ERDA 0524 dated 1975 and 1977. Without documentation to the contrary, it is suggested that NCRP Handbooks and AEC Manuals were used between these two dates.

4.2 Historical Radiological Protection Programs at the PDGP

Most of the information obtained on the radiation protection at the Paducah Gaseous Diffusion Plant program comes from a 1961 report by R.A. Winkel titled "Paducah Plant Health Physics Program" [34]. In this report it is stated that line supervision has the “primary responsibility for the protection of personnel against hazards associated with radioactive materials.” The purpose of the Health Physics and Hygiene Department was to provide a monitoring service, maintain exposure records and “furnish line supervision with advice, information and training aid on radiation or uranium toxicity health hazards” and “recommends plant guides for controlling employee exposure.” This suggests that radiation protection was the responsibility of line supervision; the health physicist(s) appeared to play advisory or secondary roles and may have had little authority to enforce its recommendations concerning personnel protection.

The early radiological monitoring procedures and methods were obtained from documents dating to the early 1960's. There were three major areas of monitoring: personnel exposure monitoring, work area monitoring and shipment/scrap monitoring. The PGDP health physics and industrial hygiene program procedures were based on recommendations of the NCRP, National Radiation Council, the American Conference of Governmental Industrial Hygienists and the AIHI Hygienic Guide Series [38].

4.2.1 Personnel Exposure Monitoring

Two methods, external dosimeters and bioassay measurements determined personnel exposure. The resulting measurements were recorded by Data Processing. At the end of each quarter, the calendar year quarterly and accumulated annual exposure reports respectively were prepared by Data Processing. Plant Records maintained the quarterly and annual reports as a permanent record. Data processing also prepared individual exposure records for each employee, which contained the annual dose since being hired. This report was filed in the employee’s medical record [2]. The results of the external exposure and bioassay monitoring are covered in Sections 6 and 7 of this report.

4.2.1.1 External Dosimeters

Prior to 1961, select groups of employees considered to have the potential for radiation exposures were issued film badges. After 1960, all employees were issued two combination security/film badges. From 1960 to 1961 the number of workers issued film badges went from 526 to 1690. One badge was to be used while the other was being processed. The length for badge rotation depended on the exposure potential of the employee. In the early years of the plant operations, some groups of personnel with increased potential of radiation exposure were put on a weekly badge program. Workers with an exposure potential below the quarterly radiation protection guidelines were on a three-month cycle. Buildings C-340, C-400 and C-410 had increased potentials for radiation exposure so workers in these areas had a one month cycle to ensure employees did not exceed the quarterly exposure limits [39].

The employee's security badge number identified the film. In the event that a badge was issued to a Paducah AEC employee the security badge number was prefixed with a B 01- to avoid duplication of numbers. Temporary visitor or replacement lost badges were prefixed by A- and followed by a sequential numbering. Calibration and test film was identified with a C- prefix.

The badges were loaded with DuPont Dosimeter Film Packet 544 that contains film component 555, with a range of 15 mrad to 10 rad, and film component 834 with a range of 5 rad to 500 rad. The badge was also loaded with a Kodak Neutron Monitoring Film type A packet with a range of 20 mrad to 10 rad. If needed changing the development time could extend the film range.

Each batch of received film was calibrated for gamma and beta exposures. Using a 330 mCi Cobalt-60 source calibration films were exposed to doses of 50, 195, 540, 1500 and 4000 mrad. The film badge positions had been selected based on results from a National Bureau of Standards radium source. In preparation for a possible criticality incident emergency calibrations were done for 3, 5, 10, 30, 100, 300, 500, 700 and 1000 rad. The emergency calibration films were stored in a desiccator. If no incidents occurred the film was replaced every six months. Beta response was calibrated by placing a film badge face down on uranium metal (240 mrem/hr surface dose) for varying time to produce equivalent absorbed doses of 30, 100, 300, 1000, 2000, 3000, 5000 and 7500 mrad.

Film was developed in batches consisting of the sensitive film (film type 555) from badges along with two films for each dose level and two unexposed films. The high range film (film type 834) was stored unless analysis of the sensitive film showed a need for a high dose measurement. Film developing was done under the following parameters and procedures: temperature 68 – 69 °F, 3 minutes in developer, 1 minute rinse, 10 minute fixer, 30 minute rinse and 2 hours drying [39].

After using the control film to zero the instrument, a Weston Model 877 Densitometer, Health Protection Type, was used to measure the transmission density of the film [39]. A reading was taken for the open window area of the film first. If the open window region had a reading of zero the exposure dose was zero and no further reading was required. If the open window region measured a response then the region under the cadmium shield was also read.

Calibration curves were generated from the calibration film. For exclusively beta and gamma exposure, the doses were read directly from the beta and gamma calibration curves. For mixed exposures, the gamma dose was read directly from the gamma calibration curve using the shielded density reading. The corresponding open window response to this gamma density was noted for an open window region. The corresponding gamma density was then subtracted from the open window measurement and the resulting value was the beta exposure. Values for beta dose (rads) and beta + gamma dose (rads) were sent to Data Processing for quarterly and annual reports as mentioned previously.

The transition from film badges to thermoluminescence dosimeters [TLDs] occurred in the early 1980's. TLDs are more sensitive than film badges.

4.2.1.2 *In Vitro* Bioassay

In vitro bioassay sampling at the PGDP involved the collection of a urine sample that was then analyzed for the presence of radioactive material. This method was primarily used to detect uranium, but on some occasions urine was also analyzed for plutonium and neptunium. The results of the *in vitro* bioassay measurements are used to estimate the amount of radioactive material taken into the body. From this estimated intake doses can be assessed to assure that workers do not exceed limits of exposure. *In vitro* bioassay sampling at the PGDP involved the collection of a spot urine sample that was then analyzed for the presence of uranium. Very limited urinalysis sampling was done to monitor for neptunium and plutonium. As noted in the Phase II report [2], neptunium, at the trace concentrations found in reactor tails feed material, "was not a significant radiological hazard". "At such levels, the controls applied to protect against uranium exposure provided ample protection from neptunium." However, "They (Paducah Health Physics Staff) knew that traditional uranium controls would not be sufficient for areas where neptunium would concentrate …". [2]

In 1962, the Health Physics and Hygiene Department detailed the early bioassay program from 1953 to 1962 [40]. Information on the program that existed through June of 1982 was presented in a memo dated 1983 [41]. Table 4.3 summarizes the levels of uranium in the urine that would require that a worker be recalled for additional testing and levels that would require that the worker be placed on "restriction". Restricted employees were moved to areas of the plant with reduced exposure potential. The recall schedule, the exposure limits and the levels required for work restriction changed with time over the plant history. The routine weekly re-checks were usually done on Monday mornings (Monday Morning Recall).

The frequency of routine sample collection for uranium bioassay was determined from the Master Schedule. A copy of the Master Schedule was not available but the frequency of sample collection varied between a maximum frequency of every 4 weeks for personnel routinely working in buildings C-310, C-315, C-340, C-400 and C-410 to a minimum frequency of yearly for lower risk locations. Samples were also collected following incidents or accidents, upon termination of employment or if a recall was decided from previous results.

Table 4.3. Urine bioassay program for Uranium. Action points: recall and restrictions.

Period	Recall	Restriction
1952 - 1955	Single sample > 10 µg U/L Recalled until < 10 µg U/L	Two consecutive samples = 10 µg U/L
1956 - 1961	Single sample > 10 µg U/L if not scheduled for sample in 3 months	Single sample = 100 µg U/L
	Single sample > 40 µg U/L if not scheduled for sample in one month	Single sample > 12 µg U/day
	Three consecutive samples = 0.01 mg U/L. Recalled until 2 samples < 6 µg U/day.	
1962 - 1969	Single sample >60 µg U/L	Single sample >870 µg U/L
	Quarterly avg. samples >33 µg U/L	Quarterly avg. samples >60 µg U/L
	Three consecutive samples >12 µg U/L. Recalled until two samples <12 µg U/day	>20 µg U/day
1969 - 1976	Single sample >60 µg U/L	Single sample >870 µg U/L
	Quarterly avg. samples >33 µg U/L. Recalled until <20 µg U/L	Quarterly avg. samples >60 µg U/L
1977 - 6/82	Single sample >33 µg U/L	Single sample >870 µg U/L
	Three consecutive samples >19-33 µg U/L. Recalled until <20 µg U/L	
6/82	For soluble Uranium <5% U-235 >50 µg U/L	Soluble Uranium, >200 µg U/L
	For insoluble Uranium, >20 µg U/L. Recalled until <20 µg U/L.	Insoluble Uranium, >90 µg U/L

PGDP personnel performed on-site analysis of uranium bioassay samples. The urine samples were measured for specific gravity, pH, sugar, and albumin levels. The uranium content was measured using a previously zeroed and calibrated fluorimeter. A minimum of two aliquots was measured from each sample. The measurements were averaged, the blank measurement subtracted and the difference multiplied by the machine, factor which was calculated from known uranium calibration solutions. The resulting product was recorded as the uranium in urine value. Typical detection limits for fluorimetry in the early years were around 0.005 mg U/L. A draw back of the fluorimetry method was a lack of isotope determination.

Uranium was the only nuclide routinely measured using bioassays; however a limited number of samples were sent to external facilities for measurement of plutonium and neptunium.

4.2.2 Work Area Monitoring

Work area monitoring is important in radiological safety to identify areas of releases or contamination. Periodic area monitoring can detect contaminants that would be difficult to detect later by bioassay and can determine the sources of exposure detected by film badges. Work area monitoring was conducted at PGDP by air sampling and area surveys.

4.2.2.1 Air Sampling

Air sampling was used to monitor for both chemical and radiological airborne concentrations. Spot air sampling was done to monitor specific areas or during maintenance jobs. Samples were collected with a Staplex® high volume air sampler at a flow rate of 14 to 18 cfm (81 to 105 cm/sec face velocity) using a Whatman #41 filter paper [42]. The period of sample collection was likely job dependent, but is not readily discerned from the currently available documents. Samples were normally measured only for alpha activity and the results were to be reported to the appropriate supervisor.

Fixed continuous air monitors collected samples of general air contamination for a given location. Fixed air sampling devices were located as follows:

C-310	Product Withdrawal Room
C-315	Tails Withdrawal Room
C-340	Bomb Filling Area
C-340	Powder Unit 6th Floor
C-400	Ash Processing Area
C-400	Near Hand Decontamination Tables
C-400	Near Calciner
C-400	Trace Cubicle
C-410	East Tower Area
C-410	West Tower Area
C-420	2nd Floor Process Area
C-710	Laboratory
C-720	Compressor Shop
C-720	Converter Shop

Samples were collected using Whatman #40 filter paper at a flow rate of 0.3 to 0.7 cfm (28 to 65 cm/sec face velocity) for 8, 16 or 24 hour sampling periods [42]. Results from the fixed monitors were tabulated and a copy was sent to the Health Physics Department. Specific jobs or operations could also be monitored using a Research Appliance Co. automatic changing roll tape filter which used Whatman #4 filter paper operating at a flow rate of 0.1 to 0.2 cfm (9 to 19 cm/s face velocity). The portable sampler could be operated for collection times of 2 to 24 hour duration. Results would be calculated and reported to appropriate supervision. Eight environmental air samplers were also operated. The environmental samplers were located North, South, East and West of the plant at the perimeter fence and another sampler in the four directions one mile outside the fence. Environmental samplers used a 2-inch membrane filter type AM-4 at a flow rate of 0.3 cfm (11 cm/sec face velocity) and operated for one week durations. Environmental sampling results were tabulated and reported in the monthly Health Physics and Hygiene Summary report.

Alpha counting of filter paper was done on parallel plate counters. Results were reported as counts per minute (cpm) for spot samplers and disintegrations per minute (dpm) for both portable and fixed continuous samples. Beta and gamma activity was measured using a shielded Geiger-Muller tube and reported as dpm. The measured activities were calculated and reported as dpm/meter^3. These results are incorporated into the general exposure profiles (Section 7.2) and worker exposure scenarios (Section 6).

4.2.2.2 Area Surveys

Area monitoring surveys were performed for alpha contamination and also for beta/gamma contamination. Alpha monitoring was performed using a paper towel to take a smear over an area of 100 cm^2. The smears were counted and reported as cpm/100 cm^2 transferable contamination. Surveying of personnel consisted of checking clothing, shoe tops and hands. Alpha survey results were summarized and were reported to the appropriate supervision. From descriptions provided by the workers, however, the surveying of personnel was not routine, rather only conducted on special occasions. A number of survey instruments where available [43] and the instrument name, range and a brief description are in the following Table 4.4.

Table 4.4 Instruments for area surveys at PDGP.

Name	Type	Range c/m/100 cm^2
Samson Alpha Survey Meter	Air Ionization Chamber	Up to 12,500
Modified Samson Alpha Survey Meter	Air Ionization Chamber	Up to 125,000
Gas Proportional Alpha Counter Eberline Model PAC-3G	Propane gas proportional counter 61 cm^2 surface area	Up to 160,000
Junos (Standard and High Range)	Air Ionization Chamber 83 cm^2 chamber area	Up to 6,000,000 or Up to 30,000,000
Parallel Plate Counters	NA	For low activity determination

Beta particle and gamma ray monitoring surveys consisted of measuring the dose rate at the surface and at one foot from a source. In areas where a number of gamma sources were present an isodose plot was made. The following table lists the available instruments for beta/gamma surveys. The dose range is based on calibration by a cobalt-60 source. To approximate a beta dose rate, the meter reading was to be multiplied by 2 [44].

Table 4.5. Instruments for beta/gamma surveys at PDGP.

Instrument	Type	Range
Juno-SRJ-6	Air Ionization Chamber	0 – 5 rad/hr
HRJ-6	Air Ionization Chamber	0 – 25 rad/hr
Modified HRJ-6	Air Ionization Chamber	0 –50 rad/hr
Nuclear Corp.	GM tube	0 – 20 mr/hr
Precision Inst. Inc.	GM tube	0 – 20 mr/hr
Eberline Inst. Co.	GM tube	0 – 200 mr/hr
FCDA CD V-700	GM tube	0 – 50 mr/hr
Cutie Pie	Ionization Chamber	0 – 5 r/hr gamma
FCDA CD V-710	Ionization Chamber	0 – 50 r/hr gamma
Radector	Ionization Chamber	0 – 50 r/hr gamma
SU-6 Pocket Radiac	Ionization Chamber	50 – 500 r/hr gamma

4.2.3 Contamination Control and Protective Equipment Programs

The Team reviewed available documentation pertaining to contamination control and protective equipment. Specifically, past Health Physics and Hygiene reports, Health Physics Inspection reports, and worker interviews were useful in getting a better description of work conditions. Additionally, the DOE Phase II report [2] provided a description of work conditions over time at the PGDP.

The Phase II report stated that the PGDP contamination control program was “ineffective through the mid 1980’s”[2]. Some examples from health physics reports and worker interviews that appear to indicate an "ineffective" contamination control program include:

1. There were times when the resulting dust covered everything in the building (C-410) including the lunchroom tables that were located in the control tower [3,4].

2. In discussing the job of unplugging blocked towers in C-410 the workers reported that they would stand under the tower and beat the plug with a steel rod. The ash would than fall out either into the barrel or onto the floor. They mentioned that on some occasions they would be covered with black soot [5].

3. Workers reported that there was almost always visible green powder on the floor in building C-410 [3]. These conditions were confirmed by various health physics inspection reports and surveys through the 1960's and 1970's [6].

Reports from workers and some health physics inspection reports indicate that respirator use was at best "inconsistent" and often considered "voluntary" [2]. Additionally, there were reports of personal clothing frequently contaminated above release limits without any corrective actions being implemented by management [2]. Some examples that show these inconsistencies include:

1. In many cases, after the fact, Health Physics recommended the use of respiratory protection devices for specific tasks with identified high airborne radioactive material concentrations. However, the evidence suggests that although line management acknowledged receipt of those recommendations, they were not always implemented [2].

2. Work was reportedly routinely conducted without the benefit of respirators on open cascade components in process buildings that were known to contain transuranic compounds. Respiratory protection was not always used during UF_6 releases in process areas, and it was common for operators or Operations supervisors to enter the area of an active UF_6 release without respiratory protection or other PPE in order to stop the release [2,3].

3. It is apparent that into the late 70's guidance to employees allowed workers to choose whether to use a respirator, and what type, based on their perception of odor or visible fumes in the work area. It is evident that respirator use during this period remained largely voluntary, since the guidance only recommended that personnel leave the area of air contamination when necessary to obtain proper respiratory protection for the contaminant encountered [2].

4. Use of company issued coveralls was limited to certain work areas. In most areas personal clothing was used. Evidence suggests that Paducah personnel routinely exceeded personal clothing contamination limits without any corrective actions being implemented by management [2].

5.0 PRIOR RADIOLOGICAL AND HEALTH ASSESSMENTS AT GASEOUS DIFFUSION PLANTS

Synopsis *¾ Several prior exposure assessments have been done at the PGDP, and include an internal and several external reports. Of particular interest were possible historical and contemporary exposures to plutonium and neptunium. The primary internal report, titled "Exposure Assessment - Uranium Recycle Materials in the Paducah Feed Plant" was put out in draft form in 1987. This document was valuable from the historical perspective, although very preliminary in nature. While some of the dosimetry has been difficult for the present Team to confirm and reconstruct, the document does identify groups of workers, processes and locations where the workers had the potential for increased radiation exposure. An external exposure assessment was also conducted in 1992 and some workers were selected for bioassay of TRUs. The report assumes what are defined as some worst case scenarios (based on 1990 air monitoring data) and suggests that the probable exposures to TRUs would not likely exceed regulatory limits. The Team had difficulty confirming and reconstructing some aspects of this report, but does generally agree with the identification of the work areas that had increased potential for radiation exposures. A re-evaluation of this report was done by another outside group in 1993 and concluded that the writers of the 1992 report had made some assumptions that may have overestimated the committed effective doses to selected organs (e.g. bone). The present Team has done some similar modeling of internal doses based on available documents, and these preliminary results are presented in Sections 7.5 of this document.*

5.1 Introduction and Overview

During the 50-year operation of the Paducah Gaseous Diffusion Plant, there have been several radiological assessments conducted. Some of the assessments and evaluations led to several significant reports and documents that were used to guide the health physics programs implementation and management.

Because the prior radiological assessments are important in evaluating the historical aspects of worker radiation exposures at the plant, the Team reviewed them.

5.2 Prior Radiological Assessments at the PGDP

5.2.1 Exposure Assessment - Uranium Recycle Materials in the Paducah Feed Plant

Sponsor: Martin Marietta Energy Systems, Inc. Date of document: July 23, 1987. Author: R. C. Baker with cover letter from D.J. Bostock [25].

This is a "draft" report that apparently was never finalized, but was circulated internally. The report describes the input material, process description, employee assignments, work areas and hours, nuclides in feed plant aerosols, and estimates on annual airborne radiation exposure.

The report estimated that ^{239}Pu and ^{237}Np provided 12% of the reported 1.54 rem average annual combined total external dose and 50-year committed effective dose equivalent. R.C. Baker performed the calculations based on average air concentrations and particle size of the aerosols. Air sampling data used within the report appears to be based on fixed air sampling data collected during routine operations within the C-410/420 building. Potential TRU exposures from other tasks were not calculated. An ICRP model (ICRP-30, Part I) was employed for calculating doses.

This document was a "draft" and as such must be considered as not "final". The report lacked supporting reference documents or explanations, thus the data and information has to be taken at "face value". There were many assumptions made in the model that was employed, and the basis for some of the assumptions was not clear and could be questioned based on other documentation. However, the report does identify some of the locations having the potential for increased radiation exposure and the worker groups that may have been exposed to them and as such, is considered to be valuable document in the exposure assessment effort. Some of the jobs/tasks that were addressed in this report include the feed plant operators, $U0_3$ powder handling, green salt plant (C-420), fluorination tower operators and cold trap and refrigeration systems maintenance. Some of the worker groups that were identified in this report were also confirmed in the present Exposure Assessment.

5.2.2 Personnel Exposure Potential to Transuranic Materials at the PGDP ("IT Report")

Sponsor: Martin Marietta Energy Systems, Inc. Date of document: September 2, 1992. Author: IT Corporation / Nuclear Sciences, Carol D. Berger, CHP [8]

This study used three methods to estimate historical exposures to uranium, plutonium, and neptunium at the PGDP. The historical uranium urinalysis data, 1989-1991 air sampling data, and 1991 fecal bioassay data for a small selection of employees (16 plus 2 control – most of which were hired in the mid to late 1970s) were used separately to estimate historic exposures to uranium, plutonium, and neptunium. Using these three approaches, the authors calculated the "fraction of significant exposure". The "Significant Exposure" level was defined at an intake of 100% of the Annual Limit on Intake for each of the nuclides, an exposure of 2000 Derived Air Concentration-hours, or a committed effective dose equivalent of 5 rem. In each case the reported fraction of significant exposure was either 0.2 or 0.21. The team could not confirm these calculations.

Some serious concerns were noted regarding the study methodology including: 1) the use of average values of statistically insignificant numbers (including negative bioassay results) to determine doses, 2) the determination of dose assuming an acute intake 1, 5 and 10 years before the bioassay sample does not address the question of what transuranic intakes might have been 16-39 years earlier, 3) the workers selected for inclusion within the fecal bioassay study were hired in the mid-1970s however, the majority of the reactor return work was conducted from 1953 through 1977, 4) dose estimates based on uranium urinalysis results were based on only two years of uranium urine data, and 5) dose estimates based on air sampling were based on air sampling data collected from 1989-1991. It is unlikely that samples collected during this time

period represent air concentrations from 1953 to the late 1970s. The items noted above contributed to the limited value of this report for the current exposure assessment.

6.0 WORKER EXPOSURE SCENARIOS AND GENERAL RANKING OF POTENTIAL RADIATION EXPOSURES BY OCCUPATION, TASK AND LOCATION

Synopsis ¾ The ranking of the potential for worker radiation exposures was based on available documentation, worker risk mapping sessions, and worker interview transcripts. The relative rankings are based on potential radiation exposures found to be associated with job tasks and/or job groups (departments) and are not necessarily indicative of individual worker exposures.

In general the categories, which had increased potential for exposures from external radiation, were similar to those for internal radiation.. The jobs/tasks that appear to involve the greatest potential for radiation exposure included ash handling (C-410), cylinder heel cleaning (C-400), derby processing (C-340), pulverizer operations (C-400), certain maintenance operations on the fluorination towers (C-410), maintenance on cascade equipment (Cascades), cleaning of air filters (baghouses for C-400, C-410, C-420, C-340), converter maintenance (C-720), flange grinding (C-340, C-400, C-410, C-420), maintenance of the hydrogenation towers (C-340) and decontamination building cleaning operations (C-400). Jobs/tasks that were classified as having moderate potential radiation exposures include cascade operators and instrument mechanics (cascades), green salt sweeping (C-410, C-420), disassembly of compressor (C-720), disassembly of block valves (C-720), drumming of green salt (C-340), and baghouse cleaning for cascades (C-310, C-315). Other jobs/tasks were considered to have lower potential for worker radiation exposure. The exceptions to the above were incidents, accidents and other excursions where there was the potential for higher, usually shorter-term radiation exposures. In the early years of the plant in particular, incidents of this nature were not uncommon. In addition, due to lack of aggressive contamination control programs, contamination from operations identified above presented potential exposures to surrounding work areas. Further, legacy contamination generated from these operations could have posed a potential radiation exposure to workers in later years.

6.1 Overview and Limitations

Information regarding potential worker exposures comes from the available historical documentation, previous assessment reports, and worker interviews (DOE transcripts and group interviews conducted by CPS). The worker interviews provided an oral history of the working conditions in the plant, a description of the tasks and how they were performed, the occurrence of unusual situations, information regarding the use of personnel protection equipment, and general plant attitudes about the potential for radiation exposure. One hundred and fifty workers and former workers were interviewed in conjunction with the DOE Phase II Investigation [2]. It was determined that about 40 of these individuals had actually worked in areas that were considered to be associated with higher potential for radiation exposures. About 40 other individuals had worked in areas where moderate radiation exposures may have occurred.

Based on the tasks and jobs identified in historical documents, previous assessment reports, and worker interviews, the Team developed exposure scenarios (Appendix F), which outline the likely sources of radiation exposure along with the work practices and work conditions associated with the jobs and tasks.

Additionally, the Team evaluated the potential for radiation exposure for the identified jobs and tasks. There are some cautions on the interpretation of the "scenarios" presented in this section. First, because a potential for radiation exposure existed, it does not necessarily imply that workers were thus "exposed". Likewise, workers could have been "exposed" performing duties or at locations not identified in this report. The intent here is to provide a general overview and first pass ranking of the potential for exposure to both external radiation (e.g. gamma rays and beta particles) and internal radiation (e.g., ingestion or inhalation of uranium, plutonium and neptunium).

6.2 Evaluation of potential for radiation exposures

The following table summarizes the potential for increased radiation exposure for many of the important jobs and tasks performed in the PGDP during the years 1953 to 1978. Table 6.1 presents a ranking of tasks by potential for increased radiation exposure. This ranking is based on perceived hazard by the team and only indicates relative hazard, not necessarily a quantitative hazard. Table 6.1 indicates that many of the jobs and tasks associated with high potential for increased radiation exposure were performed in buildings C-410/420 and C-340. In 1978 production in these buildings was phased out. Legacy contamination from these processes would, however, still have the potential for radiological exposure to workers entering these areas. To the extent possible, the rankings shown in Table 6.1 were compared against exposure data from the provided dosimetry databases and historical health physics reports and found to be consistent. A direct comparison of the listed jobs and tasks with data from the database was difficult since the electronic data was only linked to department numbers and not to jobs, tasks, or buildings. Review of the data identified in the electronic database is included in section 7.

Table 6.1. Relative Potential for Worker Radiation Exposures

High Potential for Increased Radiation Exposure	
Ash handling	C-410
Cylinder heel cleaning	C-400
Derby processing	C-340
Pulverizer operations	C-400
Unplugging fluorination towers	C-410
Unplugging and maintaining C-420 equipment	C-420
Maintaining cascade equipment	Cascades
Baghouse cleaning	C-400, C-410, C-420, C-340
Cleaning and maintaining hydrogenation towers	C-340
Converter Maintenance	C-720, C-409, C-400

Flange grinding	C-340, C-400, C-410, C-420
Decontamination Bldg. Cleaning Operations	C-400

Moderate Potential for Increased Radiation Exposure

Cascade operators	Cascades
Instrument mechanics	All
Green salt sweeping	C-410, C-420
Disassembly of compressors	C-720
Disassembly of block valves	C-720
Drumming green salt	C-340
Baghouse cleaning	Cascades, C-310, C-315
Chemistry Laboratory	C-710
Machining	C-720
Electrical	All
Fabrication	C-720
Crawling cell and bypass housing	Cascade buildings
Product withdrawal	C-310
Tails withdrawal	C-315
Crane operation	C-400, C-410, C-420, C-340
Replacement of UF_6 cylinder valve	outside C-400
Uranium recovery (solvent extract.)	C-400
Welding	C-410, C-420, C-720

Low Potential for Increased Radiation Exposure

Drum crushing	C-746
Building access	C-340
Guard patrolling	All
Maintenance on roof	C-340
Midnight negatives	cascades
Smelting	C-746
Burial of pyrophoric uranium in landfills	C-749
Grounds keeping	All
Lubrication	All
Spraying cooling towers w/ fungicide	Cooling towers
Cooling tower operations	Cooling towers

Special Incidences or Activities - High Potential for Increased Radiation Exposure

C-310 fire, 1956	C-310
C-337 fire, 1962	C-337
C-340, explosion and fire, 1962	C-340
Two workers overexposed, 1968	unknown location
C-315 fire, 1978	C-315

Cascade improvement program, 1958-1962	Cascades
Cascade improvement program, 1974-1982	Cascades
Neptunium production	C-400
Materials Releases	Many

There were some jobs that had a greater potential of radioactive materials being ingested or inhaled. These included the processing and conversion to UF_4, fluorination, powder pulverization, various decontamination activities and most of the operations associated with uranium metal production. Additionally some jobs, particularly around the ash receivers, had greater potential radiation exposures to beta and gamma radiation from concentrated uranium daughters and various fission products. There was also increased potential for dust inhalation around the ash receivers. These operations were all carried out in C-400 (decontamination building), C-410, C-420 (feed plants) and the metals building (C-340).

Except when major remodeling was being done on the cascades (C-331, C-333, C-335 and C-337), they appear to have had fewer potential sources of radiation than the buildings mentioned above (C-340, C-400, C-410, C-420). Much of this was due to the negative pressure that was maintained on most of the cascade piping. Because of this, leaks resulted in atmospheric air being sucked into the system rather than UF_6 gas being vented to the outside. There were enough exceptions, however, to periodically create a potentially higher radiation exposure. Examples were compressor maintenance, valve repair, etc. When these occurred, the system would be opened up with resulting increased potential for exposure to operators and maintenance mechanics.

Based on worker interviews, the potential for exposures in the cascades increased during the cascade improvement and upgrade programs of 1958-1962 and 1974-1982**.** One interesting practice was what was known as "crawling the pipes". This occurred when the cascade system was opened up for maintenance or repairs. Operators from the cascades or C-400 would be sent into the pipes to remove debris. A variation on this occurred during the cascade upgrade programs when decontamination workers scrubbed out the pipes. At first glance, this should have been a very risky practice because of the presence of uranyl fluoride. However, it appears that unless an aerosol was created and inhaled, the risk may not have been as high as perceived. On the other hand, there were maintenance operations that did create dust and based on some of the analyses reported for TRU activities in dust samples, there could have been some potential exposures to radioactive materials.

The product and tails withdrawal buildings form a special case. When the PGDP first started operations, C-315 (tails withdrawal) was stated by some workers to be the most "hazardous" building on the site as far as exposure to radioactivity was concerned. The worker interviews indicate that with time, the conditions in this building improved and it was their perception that it was also safer.

The trade's personnel, including electricians, welders, machinists, etc., were potentially exposed to radiation when performing maintenance on equipment where radioactive materials may have accumulated.

Most of the other personnel do not appear to have been routinely at risk, except possibly during accidents, incidents or materials releases or possibly from exposures to legacy contamination from prior operations which were not well characterized or controlled [2].

6.3 Descriptive Exposure Scenarios

For some of the primary occupations and or assignments where the exposure potential was generally perceived by the Team to be the greatest, a scenario for these "occupations" is provided in Appendix F and includes the following:

Table 6.2. Exposure Scenarios

Operations	Workers	Location
Ash receivers and fluorination Towers	Operators and maintenance mechanics	C-410 Feed plant
Cylinder heels	Operators, cylinder movers	C-410 Feed plant
Cylinder heels cleaning	Operators	C-410 Feed plant
Derby processing	Operators	C-340 Metals
Pulverizer operations	Operators and maintenance mechanics	C-400
Unplugging and maintaining oxide Conversion equipment	Operators and maintenance mechanics	C-420 Oxide Conversion Plant
Cascade maintenance	Operators and maintenance mechanics	C-331, C-333, C-335, C-337
Baghouse cleaning	Operators	C-400, C-410 C-420, C-340
Hydrogenation tower cleaning and maintenance	Operators and maintenance mechanics	C-340 Metals
Spray cleaning operations	Operators	C-400
Flange grinding	Maintenance mechanics and machinists	C-720 Cascades
Green salt sweeping and Drumming	Operators and janitors	C-400, C-410 C-420, C-340
Disassembly of compressors and Block valves	Maintenance mechanics, compressor mechanics	C-720
Fluorine cooling tower Carpentry	Carpenter	C-340
Baghouse cleaning (cascades)	Operators	C-331, C-333 C-335, C-337

Operations	Workers	Location
Instrument maintenance	Instrument mechanics	Cascades C-400, C-410, C-420, C-340 C-310, C-315
Machine Shop	Machinists	C-720
Electrical work All		Electricians
Product withdrawal	Operators	C-310 Product Withdrawal
Tails withdrawal	Operators	C-315 Tails withdrawal
Crawling the pipes	Operators, welders	C-331, C-333, C-335, C-337 Cascades
Midnight negatives	Everyone outside the cascades	Vicinity of Cascades
Cooling tower operators	Staff	Water towers
Fire suppression	Firefighters	C-310, C-315 C-720
Cascade improvement	Operators and maintenance mechanics	C-331, C-333 C-335, C-337

7.0 INFORMATION REGARDING WORKER EXPOSURES BASED ON DATABASES, AIR SAMPLING RECORDS AND HEALTH PHYSICS REPORTS

Synopsis *¾ Based on this preliminary review it is estimated that 2,500 to 4,000 workers worked in areas with moderate to high potential for increased radiation exposure. From the databases, it was noted that about 200 workers received in excess of 1 rem/yr from external radiation exposures. Departments and work areas with potential for elevated worker radiation exposures were identified from worker interviews, dosimetry database queries and historic health physics summary reports and inspection reports. Areas identified included: Feed Plant (C-410/420), Decontamination Building (C-400), Metals Building (C-340), and the Cascade Buildings (C-331, C-333, C-335, C-337). Primary Departments identified included: Process Operators (Depts. 5730, 5646, 5751), Chemical Operators (Depts. 5760, 5785), Maintenance Mechanics (Depts. 5002, 5027, 5034, 5035, 5048), Instrument Mechanics (Dept. 5075), and Electricians (Dept. 5077).*

Worker interviews emphasized that contamination control was limited. For example, personnel monitoring (frisking) did not occur routinely until the 1990s. Respirator usage was reported as inconsistent at best. Workers noted that radiation monitoring badge readings in excess of the limits were in many cases assumed to be invalid. Some of these issues were included in the Phase II report [2].

Preliminary "spot checks" of the provided electronic dosimetry databases indicate that the electronic data may be incomplete and/or inaccurate. A quality assurance/quality control (QA/QC) check of the worker radiation exposure electronic databases is recommended. This QA/QC check should provide additional information concerning the accuracy of the data entries and implications to the relative ranking of the potential for increased worker radiation exposures and the conclusions of this report. Further, it is apparent that some elevated worker radiation exposure data identified in source documents (Health Physics reports) are not included within electronic database tables. Some of the exposures from incidents and accidents may also not have been recorded in the database. The Team strongly recommends the review of the original dosimetry records. All parties involved from the outset of this study recognized the need for this review.

Finally, it should be noted that from 1953-1961, only workers believed to have the potential for increased radiation exposures were monitored. It is apparent from subsequent data that some exposures received during this time frame may have not been measured.

7.1 Overview and limitations

Results of personal external radiation exposure measurements, uranium urinalyses, and *in vivo* counting results were tabulated in unverified databases supplied by the contractor. The contractor, the Team and all other parties involved recognized the following limitations in the use of these databases, such as:

- While early Health Physics reports indicate that limited *in vitro* bioassay monitoring for transuranics was conducted, there are no transuranic urinalysis data in the electronic databases prior to 1989.
- The historical urinalysis databases did not indicate the type of sample (routine, special, etc.) that was collected, the solubility class or enrichment, when applicable, of material being monitored.
- The databases have not been verified against any of the original records.
- The databases have not had any QA/QC evaluations.
- The databases are not complete, for example, it was determined that at least some elevated data from exposures as a result of incidents and accidents were not included in the electronic database. The databases may contain data entry errors.
- Some of the units used in the databases are not clearly documented.
- Not all department numbers found in the Health Physics reports could be correlated with the department numbers recorded in the electronic databases.
- Adequate quantitative information regarding detection limits of the *in vivo* and *in vitro* bioassay data was unavailable and prevented quantitative interpretation of these measurements.

A recent verification effort of the external dosimetry databases ("History Tape") showed a large number of discrepancies. [47]

Based on the above, the information in the databases should not be used at this time to estimate individual worker doses. A QA/QC check of the PGDP worker radiation exposure electronic databases is recommended. This QA/QC check should identify the implications of this new information to the relative ranking of the potential for increased radiation exposure to workers and conclusions of this report.

7.2 Available Radiological Records

In performing this preliminary assessment of historical worker radiation exposures at the PGDP, the Team used several sources of information to gain an understanding of the types and levels of radiation exposures encountered in various buildings, operations, jobs, and tasks. During the limited data gathering phase of the project the Team identified and obtained sources of information including: 1) dosimetry databases, 2) previous exposure assessment reports, 3) Health Physics Reports, and 4) worker interviews.

Information obtained from worker interviews was used to qualitatively rank jobs/tasks based on potential for increased radiation exposure (Section 6). The quantitative data from the dosimetry databases, previous assessment reports, and historical health physics reports were used for the exposure rankings and estimates included in this section of the report. A summary of the available quantitative data is included in the following sections.

7.2.1 Dosimetry databases

The dosimetry databases provided for the PGDP site consisted of 31 separate tables. A summary

of the data tables and a brief description of each are provided within Table 7.1. The data tables listed in bold type are those that were most often used in this report.

Table 7.1. Available electronic databases for this assessment

Data Table	Timeframe	Summary of Contents	No. of Records
BDMS_INTERNAL_DOSE	1997-1998	Internal doses (CEDE, mrem)	2688
BDMS_PARTICIPANT_APPOINTMENT_DATA	1993-1997	Urinalysis results (dpm/sample)	945
BJC_INTERNAL_DOSE	1997-1998	Internal doses (CEDE, CDE, mrem)	387
DRS_89_THRU_96	1989-1996	External doses (deep, shallow doses, mrem)	64758
DRS_97_THRU_98	1997-1998	External doses (deep, shallow doses, mrem)	2556
Employer_Company_Codes		Department and subcontractor codes	3959
HIS20_EDD_CALCULATED_EXPOSURE	1984-1998	Calculated external doses (deep, shallow doses, mrem)	2766
HIS20_EDD_INACTIVE_IRD_EXPOSURE	1960-1998	Calculated external doses (deep, shallow doses, mrem)	110232
HIS20_IDD_AIR_RECORD	1998	Air sampling data	3
HIS20_IDD_CDE	1989-1998	Internal doses (CDE, mrem)	20117
HIS20_IDD_DOSE_RECORDS	1989-1998	Dose calculation methods	77621
HIS20_IDD_BIO_RECORDS	1989-1998	Bioassay methods	77619
HIS20_IDD_DETAIL	1989-1998	Radionuclides tested (HIS20_IDD_BIO_RECORDS)	152376
HISTORY_TAPE	**1953-1988**	**Personnel gamma and beta exposure data**	**92195**
MONITORING_TECHNIQUES_CODES		Monitoring technique codes	17
OHIS_EXTERNAL_DOSE	1981-1997	TLD whole body and shallow dose data	79685
OHIS_EXTREMITY_DOSE	1990-1995	Extremity dose data	1374
OHIS_HP_SCHEDULE	1987-1998	Employee monitoring schedule	10845
OHIS_INTERNAL_DOSE	1989-1996	Assigned internal doses	61871
OHIS_INVIVO	1989-1991	Lung count data	1024
OHIS_JOB_HISTORY	1986-1998	Individual work history (Id, building, dept #)	37829
OHIS_REIRS	1989-1996	Total Effective Dose Equivalent data	19682
OHIS_URINALYSIS	1989-1997	Urinalysis results	118380
PGDP_ANALIS_URINE	1989-1997	Urinalysis test specifications	157432
PGDP_HISTORICAL_URINE	**1977-1988**	**Uranium (ug/liter) and beta (dpm/ml) urinalysis results**	**52568**
PGDP_LIMS_URINE	1997-1998	Urinalysis results (uranium, beta, fluorides, glucose, protein)	13667
Reason_Codes		Reasons for bioassay sampling	29
TEAMUP_EXTREMITY	1988-1990	Extremity and deep dose data	1015
TEAMUP_SUBCONTRACTORS	1988-1993	Extremity and deep dose data for subcontractors	4385
Historical_In Vivo_Data	**1969-1985**	**Lung count data (uranium, U-235, Tc-99, and Np-237)**	**5037**
Historical_Urinalysis_Data	**1952-1977**	**Uranium urinalysis results**	**107,074**

The terms *in vivo* and *in vitro* are used to describe the internal radiation monitoring data. *In vivo* data means that results are determined from placing a radiation detector on or near a person to detect the radiation emitted from radioactivity within the person's body or within a portion of the person's body. This can be also referred to as a direct measurement and includes whole body counts and lung counts. This technique directly measures the material in the body at the time of measurement. *In vitro* data means that a person provided a biological sample (usually urine, but it could be any excreta, feces, blood, hair or tissue) that is subsequently analyzed in a laboratory to determine the type(s) and quantity (quantities) of chemical(s) or radioactivity that is present. This is referred to as an indirect measurement. To determine the activity within the individual requires an understanding of how the material behaves in the body.

For the purposes of this report, the Team concentrated on four data tables that included the

historical urinalysis results, *in vivo* monitoring results and external monitoring results.

A. Historical Internal Data
   1. Historical *In Vivo* Data, 1969-1985, 5,037 records of whole body counts. Data was included for total uranium, enriched uranium, technetium and neptunium. This is referred to below as database "A1".
   2. Historical Urinalysis Data, 1952-1977, 107,074 urinalysis records. Results were expressed as mg U/l. This is referred to below as database "A2".

B. PGDP Dosimetry Data
   1. History Tape, 1953-1988, 92,195 dosimeter records. This is referred to below as database "B1".
   2. PGDP Historical Urine, 1977-1988, 52,568 urinalysis records for uranium in µg U/l and gross beta in dpm/l. This is referred to below as database "B2".

Database B2 was of limited use because only values below 99 µg U/l of urine are included, which may have been a truncation error. The higher values may have been reported in another database that the Team did not receive. The Team found and documented a number of discrepancies, indicating that a QA/QC evaluation of the database would be appropriate. An example of such a discrepancy is an incident report of a 1986 release that occurred in C-720 indicating that several individuals received increased exposures. The two highest urine samples were listed as 13 mg U/l and 5 mg U/l [45]. Several elevated urine samples recorded in the incident report, including the results of 13 mg U/l and 5 mg U/l were not included in the database B2.

The data within database A2 do not indicate the type of sample (i.e., routine, special, physical, etc.). There are also deficiencies such as missing data from this database that were found in the HP monthly reports, especially for the 1950's. For example, a January 1953 report [46] describes the following incident: a material release occurred about 10:37 PM on 1/30/53, in C-410, and eight Union Carbide (plus 14 construction) workers were exposed. All 22 urine samples were positive for uranium, the average being 0.283 mg/l. The average for the eight Union Carbide workers was 0.37 mg/l, with a minimum of 0.08 mg/l and a maximum of greater than 0.8 mg/l. The average calculated from the database based on the highest 8 samples on 1/30/53 was 0.08 mg/l with a maximum of 0.25 mg/l. Further there were no samples dated 1/31/53.

The B1 database, the historical external dosimetry data ("History Tape"), has numerous discrepancies when comparing fields within the database itself. The discrepancies were noticed when comparing recorded values for "penetrating dose" and "skin dose" with "gamma exposure" and "beta exposure". The fields should conform to the following formula: "penetrating dose" equals "gamma exposure" and "skin dose" equals "gamma exposure" plus "beta exposure". A PGDP Assessment Tracking Report dated 5/23/00 indicates that there are 6,382 records within the database for which the aforementioned fields do not compare based on the above formulas. One case, mentioned in the report, indicates a 5,604 mrem gamma exposure and 0 mrem penetrating dose [47].

7.2.2 Health Physics Reports

Health Physics monthly summary reports and health physics inspection reports were used to determine airborne levels associated with various areas and tasks, estimating fractions of

transuranics associated with various operations or areas, identifying general external exposure levels associated with various operations or areas, and identifying areas, jobs, and departments with greater potential for radiation exposures. Health Physics summary reports were obtained from 1953 – 1968 [89]; however, the set of reports was not complete. Health physics investigation reports for C-410, C-420 and converter maintenance operations were identified for the period from 1961 – 1977 [54-58]. This set of reports was also incomplete. None of these reports included information specifying sampling or analytical methods.

7.2.3 Previous Assessment Reports

Previous assessment reports including the 1987 Baker report [25] and the DOE Phase II Investigation report [2] were used to determine areas and tasks of higher potential radiation exposure as well as to provide data used in some of the dose estimates included within section 7.5.

7.3 Information Related to External Doses

Synopsis ¾ The potential for increased external radiation exposure was more likely to occur in Buildings C-410/420, C-400, C-340 and C-720. Although only one external dose in excess of 5 rem in a calendar year was recorded on the provided electronic database, the provided electronic data indicate that approximately 200 individuals received external doses in excess of 1 rem in a calendar year. Health Physics Summary reports from the 1953-1959 timeframe indicate numerous badge readings in excess of established weekly plant action levels (e.g., Nov. 1956 HP report shows 13 badge readings above the plant allowable limit of 300 mrem/week, with the highest being 1010 mrem/week), but it was reported that workers were kept below regulatory limits through job rotation. Health physics reports and worker interviews identified several areas and/or jobs (primarily where uranium daughters and transuranic materials were likely to concentrate) with high area dose rates. For example, a beta-gamma dose rate as high as 105 rad/hour was identified in C-410 one foot from the Ash Receiver [48]. Worker doses were reportedly kept within regulatory limits by shortening the time spent performing tasks in these areas/jobs. Some workers indicated that badge readings in excess of the plant action level were in many cases invalidated and a dose was not assigned [33].

7.3.1 External dosimetry values from database

7.3.1.1 Departments with the greatest number of elevated recorded external doses

The average recorded cumulative dose of penetrating radiation received by the workers is derived from the recorded electronic data at PGDP and is presented by department in Table 7.2. The number of workers given in this table should approximate the number of employees in the departments during the time interval considered. Because some workers were assigned to more than one department, this Table overestimates the total number of badged workers. The primary utility of the analysis shown in Table 7.2 is to rank departments and groups of workers with recorded radiation doses. This preliminary analysis should not be used for estimating worker's cumulative external radiation exposure without further QA/QC of the data.

Table 7.2. Average recorded cumulative penetrating dose and the number of workers assigned to each department during the years 1953-1988. Data is by department and doses are in mrem.

Dept #	Description	Average cumulative dose (mrem)	Number of workers
5751	Feed Plant Operators	3,814	185
5760	Decontamination	2,788	116
5034	Feed Plant Mechanics	2,587	99
5015	Unknown	2,025	17
5676	Unknown	861	14
5730	Cascade Operators	627	578
5785	Chemical Operators	595	113
5075	Instrument.	538	245
5020	Unknown	481	17
5008	Transportation Pool	371	33
5002	Process Maintenance	364	578
5108	Environ. Control	338	48
5268	Unknown	316	236
5077	Electricians	298	318
5005	Mat. Term. Mgr	295	90
5772	PEMU Decontamination	253	22
5759	Unknown	220	4
5049	Unknown	182	12
5725	Unknown	175	20
5044	Mech. Inspection	170	113
5021	Plant Services	147	486
5770	Convert. Test	145	23
5035	Feed Plant Mechanics	143	160
5019	Unknown	142	13
5740	Nitrogen Plant	142	22
5646	Metals building	132	95
5674	Unknown	129	8
5048	Fabrication Shops	127	667
5023	Unknown	115	24
5675	Unknown	114	7
5743	Steam Plant	111	61
5027	Unknown	110	282
			Total: 4,706

From the data summarized above, it is apparent that the workers in the feed plant (operators (dept. 5751) and by the mechanics (dept. 5034)) received the highest recorded doses. The feed plant was located in buildings C-410 and C-420. The decontamination building workers (depts. 5760 and 5785) in Building C-400 also had the higher recorded doses. Next were the operators (dept. 5730) in the cascade buildings (buildings C-331, C-333, C-335, C-337).

The average recorded cumulative skin dose per worker by department is given in Table 7.3. Again, these data were obtained from the unverified database.

Table 7.3. Average recorded cumulative skin dose received by workers during the years 1953-1988. Data is by department and doses are in mrem.

Dept #	Description	Avg. Cum. Dose (mrem)	Number of Workers
5751	Feed Plant Operators	15,834	185
5760	Decontamination	12,369	116
5034	Feed Plant Mechanics	9,767	99
5676	Unknown	4,104	14
5785	Chemical Proc.	3,794	113
5015	Unknown	2,385	17
5035	Feed Plant Mechanics	1,968	160
5002	Process Maintenance	1,954	578
5730	Cascade Operators	1,824	578
5075	Instrument	1,407	245
5759	Unknown	1,315	4
5772	PEMU Decontamination	1,223	22
5674	Unknown	1,171	8
5077	Electrical	987	318
5675	Unknown	953	7
5020	Unknown	937	17
5027	Converter Shop	933	282
5005	Mat. Term. Serv.	931	90
5646	Unknown	903	95
5268	Anal. Chem.	877	235
5096	Laundry	851	31
5770	Converter Test	836	23
5024	Equipment Maintenance	586	172
5636	Unknown	581	8
5061	Unknown	575	22
5108	Environmental Control	572	48
5008	Transportation Pool	557	33
5049	Unknown	519	12
5048	Fabrication Shop	517	667
5044	Mechanical Inspect.	511	113
			Total: 4,312

The results for the skin dose follow those for the penetrating dose with minor exceptions. Once again, the workers at greatest potential for increased radiation exposure were employed in the feed plant, decontamination building and the cascades.

From the total number of workers in Tables 7.2, 7.3, and 7.6 (number of workers in the urinalysis

program by priority department), and considering that the numbers are conservative in that some workers most likely were assigned to multiple departments, it is estimated that from 2,500 to 4,000 workers worked in areas with moderate to high potential for increased radiation exposure.

7.3.1.2. Buildings with the greatest number of higher recorded external doses

Using Table 7.2 as a basis, the higher external doses appeared to have been in buildings C-400, C-410, C-420, and C-340. On the average, fewer higher doses were observed in the cascade buildings C-331, C-333, C-335, and C-337. This generally confirms the work locations for increased potential for worker radiation exposure derived from the worker interviews, plant operations and historical records as summarized in Table 7.2. There is an important caveat with these conclusions. In the early days of the plant, not all of the workers were badged, so these conclusions would bias the findings to those who were badged over the entire period (such is the case with the feed plant). Additionally, it is apparent, based on data collected from 1961-1988, that some workers from 1953-1961 would have had unrecorded exposures.

7.3.1.3. Recorded external doses over time

The average dose (in mrem) received by the workers in each year from 1953-1988, as recorded in the electronic database, was reviewed and is summarized in Table 7.4. Included in this table are the average radiation doses per worker, the maximum-recorded annual doses for any single worker for that year and the number of workers that were in the database. The minimum-recorded dose for each year was zero.

The highest average external doses were clearly received during the first decade of the operation of the plant and then generally declined after that. Some of the increases observed during the mid-1970's (e.g., 1975 and 1978) may have been the result of the second cascade improvement program (1974-1982).

Table 7.4. Average recorded doses to penetrating radiation per worker per year from 1953 to 1988. Included are the maximum exposures recorded for any single worker for that year. The doses are in mrem.

Year	Average Recorded Dose (mrem)*	Maximum Recorded Dose (mrem)	Number of Workers
53	139.8	820	223
54	283.5	1580	284
55	241.9	2500	417
56	358.6	4700	471
57	251.7	3190	669
58	185.3	3630	661
59	201.5	2360	570
60	201.1	2510	526
61	177.0	2530	1690
62	149.5	2980	1479
63	144.1	3040	1311

Year	Average Recorded Dose (mrem)*	Maximum Recorded Dose (mrem)	Number of Workers
64	73.4	1860	1219
65	34.1	1610	1128
66	31.7	1470	1138
67	49.8	1120	1143
68	61.8	1400	1241
69	73.3	1970	1270
70	41.7	840	1273
71	62.4	1380	1254
72	58.9	1760	1288
73	53.0	1830	1404
74	26.5	1030	1624
75	50.1	1049	2013
76	35.1	1224	2426
77	23.2	742	2643
78	39.9	359	2613
79	8.2	364	2487
80	18.2	344	2308
81	7.6	420	1840
82	6.5	350	1617
83	6.7	340	1452
84	9.2	420	1434
85	6.1	350	1365
86	9.6	490	1244
87	8.0	470	1275
88	6.5	720	1359

*The large number of zero values in the database would reduce the average values below what they realistically may have been.

7.3.2 Example of data available in health physics reports

Monthly Health Physics Reports or excerpts of reports were obtained for the years 1953 through 1968. These reports contain monthly dose information, including identification of workers with recorded doses that exceeded the monthly site control level. Of interest were the departments and locations where the doses exceeded the monthly control level. When these levels were documented, the workers were reportedly transferred to a different work location or department, such that their yearly exposures would remain within the regulatory limits in force at the time. Several examples were extracted from these monthly reports and generally support the categories described in Section 6 and Section 7.3.1. Table 7.5 is an example of average external doses received by the groups of workers listed in several buildings over a 2-month period of 1956.

Table 7.5. Dosimeter badge data for January and February, 1956.

Location	January, 1956 Avg. (beta+gamma) mR/week	February, 1956 Avg. (beta+gamma) mR/week
C-400 operator	72	48
C-410 operator	61	48
C-315 operator	21	12
C-410 maintenance	82	61
C-410 instrument	39	23
C-410 electrical	15	27
C-410 utility	0	8

The dosimeter badge data shows that the radiation exposure of the C-400 and C-410 operators was relatively greater than that of the C-315 operators. It can also be seen that the C-410 maintenance mechanics were at slightly higher potential for increased radiation exposure than the C-410 operators were. Relatively higher exposures were also received by some the C-410 instrument and electrical mechanics. As noted earlier in this report, not all PGDP workers wore film badges during this period.

7.4 Information Related to Internal Doses

Synopsis ¾ The Team determined that increased potential for internal radiation exposures was encountered at the PGDP in areas and operations identified within Section 6.0 of this report. It was determined that some workers could have had internal radiation exposures that would have exceeded regulatory limits. This may include on the order of 10% of the 2,500 - 4,000 workers at risk for higher exposures. Some of the areas where workers had increased potential for internal exposures included C-400, C-410/420, C-340, C-720 Converter Shop, Cascade Maintenance, etc., and were generally similar to those areas where there were increased potentials for external exposures. The electronic urinalysis data was used primarily for purposes of determining these departments and areas. The Team feels that use of this data for further assessment of dose at this stage would be premature.

The Team identified apparent inconsistencies with the electronic database and source documents. It was also reported by several workers [3] that urine samples submitted after materials releases or accidents were always given "within a half hour after the incident". If subsequent samples were not taken, intakes from these incidents may not have been identified. Some workers recollected that the follow-up samples were provided if the initial "special sample" exceeded the plant action guide level. This further raises issues regarding the use of the uranium urinalysis data for purposes of estimating intakes and cumulative doses.

To provide a preliminary estimate of internal doses at select locations available air sampling data were used along with assumed stay times. The Team concluded that internal exposures to radioactive materials for these identified tasks/areas may have, in some workers, approached or exceeded current regulatory limits.

Monitoring internal doses of uranium and particularly the TRUs typically require much greater efforts by both the worker and the employer than monitoring external doses, which are recorded on dosimeters (e.g., film badges or TLDs). While general area air monitoring provides an indication that workers may be receiving internal exposures, it has been found that this non-localized area monitoring does not always agree well with individuals' personal air sampling results or with their bioassay results. While individual bioassay data or personal air sampling results is best used to estimate individual internal doses, area air sampling can provide a rough estimate of possible internal exposures.

Bioassays require the worker to either leave the work place to be monitored with external radiation detectors (*in vivo*) or to provide excreta samples (*in vitro)* for radioactivity or fluorimetric analysis. The results of individual monitoring are interpreted based on a known or assumed exposure scenario, that must take into account the time, duration and mode (e.g., inhalation) of exposure and the physical and chemical characteristics of the material that enters the body. Using currently accepted models that describe how the material is distributed over time in the body, the time-weighted distribution of radioactive material is used to determine individual organ radiation doses, which can be reported directly or weighted and summed to provide an estimate of an individual's internal effective dose.

At the PGDP, employees with potential for higher uranium exposures were required to submit urine specimens for uranium analysis on a schedule that was determined by their perceived potential exposure. Additionally, the employees were required to undergo periodic physical examinations. Some employees were also whole body counted to assess the amount of uranium within them. The worker bioassay results for uranium are documented in the urinalysis database, the *in vivo* database and the monthly health physics summaries.

While the presence of transuranics in the feed materials was known as early as 1953, the potential for significant worker exposures to plutonium and neptunium was not fully recognized until later in the decade when it was appreciated that Paducah had a “Np problem”, but it was not known if it was serious [49]. This same memo [49] stated “There were possibly 300 people at Paducah who should be checked out but they hesitate to proceed to intensive studies because of the union’s use of this as an excuse for hazard pay.”

Actual neptunium and plutonium bioassays, especially early on, appear to have been limited to a small number of workers [34] and very limited TRU bioassay data have been identified to date. As noted earlier, none of the transuranic *in vitro* bioassay data appears in the electronic database until 1989. The earliest *in vivo* transuranic results in the database are dated 1969. Whole body count results for Tc-99 are first recorded in the database in 1977. No bioassay results for other fission products are included in the databases, but because of the lower activity to dose conversion factors, it is not believed that these other radionuclides contributed significantly to individuals' internal doses.

Because determination of internal doses from bioassay data requires a rigorous understanding of the bioassay methodologies employed and the exposure scenario, and because much of this information is currently incomplete or inadequate only a qualitative assessment of the bioassay results is provided.

7.4.1 Departments with greatest number of higher recorded uranium urinalyses results

Data from the PGDP historical urine database were used to determine the departments where higher exposures to uranium were likely to have occurred. Various scenarios were created and the data were sorted and analyzed in a variety of ways, including ranking by maximum and average uranium bioassay results.. Essentially, all approaches resulted in similar rankings (from highest measured values to lower values) by department and the tasks/jobs associated with that department, if known. The number of workers in each department, and the start and end dates (e.g. 1955 = '55') for the department are included in Table 7.6.

Table 7.6. The general ranking in descending order of the uranium bioassay results sorted by department. The number of workers and the start and end years for the department as listed in the database*.

Dept	Description	Number of Workers	Start Year	End Year	No. Years
5305	Unknown	1	55	58	4
5096	Laundry	14	53	77	25
5646	Metals	51	52	77	26
5731	Unknown	35	52	77	26
5733	Unknown	37	52	77	26
5751	Feed Plant Operators	209	51	77	27
5002	Process Maintenance	213	52	77	26
5034	Feed Plant Mechanics	126	51	77	27
5760	Decontamination	113	52	77	26
5035	Feed Plant Mechanics	59	52	77	26
5054	Unknown	1	54	60	7
5676	Unknown	7	56	62	7
5093	Fire Department	42	52	77	26
5730	Cascade Operators	316	52	77	26
5048	Fabrication Shop	261	53	77	25
5027	Convert. Shop	196	52	77	26
5075	Instrument	200	51	77	27
5077	Electrical	239	53	77	25
5268	Analytical Chemistry	202	52	77	26
5770	Conversions Test.	4	74	77	4
5772	PEMU decontamination	13	75	77	3
5784	Smelter	15	74	77	4
5785	Chemical Processing	42	68	77	10
				Total:	2,396

*From database Table A2 titled “historical urinalysis data, 1952-1977”.

The data provided for Department 5305 (Table 7.5) is likely an error in the database as only 1 worker was listed in that "department". Likewise, examination of the raw data for the laundry department indicates that its high ranking might be misleading. This is because the high value was

due to two readings of 15 mg in a single individual taken two weeks apart. Other values for this individual, either immediately prior or after these high values were less than 10 µg/l, thus these values might be erroneous.

The results show that the feed plant (dept. 5751), decontamination (depts. 5760 and 5785) and metals (dept. 5646) operators combined with maintenance mechanics (depts. 5002, 5027, 5034, 5035, and 5048) from the feed plant and probably the metals operation had the highest potential for radiation exposures.

7.4.2. Example of uranium bioassay data available in monthly health physics reports

The monthly health physics reports for the period from about 1955 through the mid-1960's included monthly or quarterly uranium bioassay results. These reports provide some information on bioassay methods, the period when the sample was collected, and the number of workers in given departments with bioassay results greater than the plant action levels in effect at the time.. Representative data for selected periods are presented here.

The following table (Table 7.7) is a summary of the urinalysis data for December 1961 to March 1962.

Table 7.7. Health Physics (HP) Summary Report of Urinalysis data for December 1961- March 1962. The data is presented in % of samples greater than 10 µg U/l, which was the action level for resampling.

	Percent of Samples > 10 µg U/l			
Dept	Dec-61	Jan-62	Feb-62	Mar-62
5001	13			
5002	49	63	70	63
5034	67	66	68	66
5048		18	8	
5075	70	72	84	60
5077	52	39	83	36
5268	19	27	6	
5730	19	26	24	15
C-340	54	71	85	79
5751	58		74	39
5760	26	13	52	46
Misc.	14	13	23	17

The above table supports the findings of the data analysis performed on the urinalysis database indicating that certain groups of workers in building C-340 and/or departments 5751, 5002, 5034, 5075 had a greater potential of radioactive material intakes.

7.4.3 *In vivo* results from database

As early as 1959, when it was realized that some workers might be at risk for exposures to TRUs, some lung counting was initiated. In 1959, "four plant personnel who worked with neptunium-237 solution" were sent for whole body counting. Their results were reported as "negative" [2], indicating that no neptunium was detected. "In March of 1962, 14 workers including those with the greatest potential exposure to neptunium and uranium were selected from various locations in the plant" [27] for whole body counting. It was reported that none had body burdens that exceeded 50% of the allowable limit for ^{237}Np [27]. As early as 1961, there were discussions of building a whole body counting facility at the PGDP to monitor workers for exposures to both neptunium and uranium [50, 51]. This whole body counter was never constructed.

Later, a mobile whole body counter was used and selected workers were assayed [2]. Some of the workers indicated that persons selected for the whole body counting were those who could be released from their duties at the time, or volunteers, rather than workers who were specifically identified based on predetermined criteria. The provided database includes whole body counting records dating from 1969 through 1986 consisting of approximately 5,000 records (approximately 3,200 include a neptunium result). Approximately 2,200 of the records were from 1980 through 1986.

The Team could not locate much technical information on the early whole body counting program, but later literature suggested some calibration and standardization deficiencies, which may have also existed with the earlier equipment and methodologies. A 1990 preliminary evaluation of the mobile whole body counter [90] notes, "the counter's capability for analysis of the above-referenced radionuclides [uranium, neptunium, plutonium and americium] with the exception of U-235, is somewhat questionable." The referenced mobile counting system included a shielded steel room and two large sodium iodide detectors [size not specified]. It is not clear from this report whether or not this was essentially the same system used in earlier years. It was noted that only efficiency calibrations for U-235 used multiple strength measurements to verify linearity. No calibration records prior to 1989 could be located. Additionally, it was noted "that the resolution of the spectrum can be insufficient to identify peaks in the presence of background radiation."

It was noted that "MDA levels have been specified for [sic] as - 83 µg for U-235 and as - 4 mg for U-238. MDAs for Np-237, Tc-99, Pu-239, and Am-241 were not specified. The indicated levels, at least for U-238, appear to be optimistic based on spectral observation at K-25 and Portsmouth."

Again the Team issues some caution in the use of the data summarized below because the databases have not been verified nor could the capabilities of the counter be determined. However, to gain some indication of the departments where relatively higher values were recorded, the Team took the highest 100 records and sorted them by department and by radionuclide. All of the departments where a worker in the top 100 was recorded are listed in Table 7.8.

Table 7.8. The number of workers with the highest 100 reported *in vivo* results of uranium, technetium and neptunium sorted by Department. The data were obtained from the electronic database for the years 1969 - 1975.

	Number of workers in top 100			
Dept.	Enriched U.	Tot. U	Tc	Np
5796 Unknown	0	0	0	1
5785 (Chem. Proc)	5	3	0	4
5770 (Converter test)	0	0	1	1
5760 (Cascade)	6	3	0	3
5751 (Feed plant)	14	17	0	1
5730 (Cascade)	13	7	9	3
5646 Unknown	4	0	0	0
5269 (Tech. Lab)	0	0	0	1
5268 (Anal. Lab)	0	0	1	0
5152 Unknown	0	1	0	0
5109 (Personnel Svc.)	0	0	1	1
5108 (Environ. Control)	0	0	1	1
5096 (Laundry)	3	1	0	1
5077 (Electrical)	1	4	1	0
5075 (Instrumentation)	3	2	1	1
5048 (Fabrication shop)	3	1	4	4
5035 (Compressor shop)	4	3	7	7
5034 Unknown	2	1	0	0
5027 (Converter shop)	2	10	9	12
5024 (Equipment maint.)	3	1	2	7
5022 (Machine shop)	0	0	1	1
5021 (Plant services)	1	0	0	0
5008 (Transportation)	1	0	0	0
5002 (Maintenance)	24	6	6	5

The departments with the largest number of workers with the highest enriched uranium *in vivo* results were maintenance, feed plant and cascades. For total uranium, the feed plant and converter shop had a larger number of elevated results. For technetium, the departments were the converter shop, cascade, compressor shop and maintenance. For neptunium, the converter shop and the maintenance workers had the higher numbers. These general departmental categories are consistent with the departments and worker categories identified in other parts of this report having increased potentials for worker radiation exposure**.**

7.5 Internal Dosimetry Modeling for Selected Operations with Higher Concentrations of Transuranics

This section describes the methods used to provide an estimate of the magnitude of internal exposures from selected operations identified with an increased transuranic source term. Internal

dose estimates are made for average and high exposure scenarios. For the purpose of this assessment and based on the PGDP recorded data, it is assumed that plutonium, neptunium, thorium-230 and uranium are the more significant contributors to internal dose for these tasks. At the end of this section less rigorous estimates of internal doses from other radioactive materials, i.e., technetium and select fission products are provided to show that they would not result in significant additional contributions to doses in these select areas.

For the transuranics, there are few *in vivo* (e.g., whole body or lung counts) or *in vitro* (e.g., urine or feces samples) measurements of the material in PGDP workers. Therefore results of area airborne radioactivity measurements are used to determine the potential dose to hypothetical workers in identified areas or performing identified tasks. It can't be stated strongly enough - these calculated doses are estimates of potential exposure to individuals and are based on average results of area air sampling data. At this time, no concerted attempt has been made to try to determine the validity of matching this air sampling data with individual worker exposures. In particular, it is frequently reported in the literature that general area air sampler results may differ by two orders of magnitude from breathing zone samplers (primarily due to a dilution effects), that air sampling results frequently don't agree with bioassay results and that dust loading of air samples may result in under reporting alpha air concentrations. In addition, information on the methods employed for counting the air sample filters was not available.

What these calculations do show is whether or not there could have been significant internal exposures, especially from transuranic materials, to workers who performed these select tasks or were in these selected areas. These calculations show that there may have been unacknowledged, but significant, internal exposures that have not to date been included in some workers' doses.

7.5.1 Air Sampling Data

The average and maximum airborne concentrations presented in Table 7.8 are based on fixed-head air sampling results from 1961 through 1977 and were derived from Health Physics Air Sampling Log books, Monthly Health Physics Inspection Reports and assessments [54-59]. The average airborne concentrations reported ranged from 5 – 500 dpm/m^3 based on approximately 135 months of data and the maximum airborne concentrations reported ranged from 225 – 5900 dpm/m^3 based on approximately 36 months of data. It should be noted that the reports often stated that maximum values were not included in the reported monthly averages. Additionally, Baker [25] notes that he made estimates of 20-year [July 1953 to 1973] average air concentrations. The air concentrations were usually reported in units of alpha disintegrations per minute per cubic meter (dpm/m^3), although occasionally the air concentration for a particular radionuclide was reported. In this latter case, it is not evident how the particular radionuclide was identified and quantified by the PGDP. In most cases, where the average values from both Baker and the Monthly Health Physics Inspection Reports were available, the results were similar.

The maximum air concentrations reported in Table 7.8 were calculated by taking the arithmetic mean of the monthly maximum airborne concentrations reported during the time period from 1961 through 1964. When results differed significantly from one reference to another, the concentration selected for use in this report was generally the one that was either supported by the most documents or the one that was closer to a middle value.

7.5.2 Radionuclide Assumptions

Baker [25] notes that equal fractions of uranium-234 and uranium-238 were in the dust in these areas, so for this assessment it is assumed that the uranium was neither enriched nor depleted. For some of the air sampling data thorium-230 and neptunium-237 results were noted. For this assessment it is assumed that all plutonium is ^{239}Pu, all neptunium is ^{237}Np, all thorium is ^{230}Th and the uranium is composed of 0.489 ^{234}U, 0.00225 ^{235}U and 0.489 ^{238}U.

Because intakes of equal activities of different radionuclides result in different doses, it is necessary to determine how much of each radionuclide was present in the mixture. For most of the areas it was assumed that the fractions of radionuclide activity reported by Baker in 1987 were reasonable. Baker notes "Data from a few samples of dust in process systems and the many analyses of feed materials were used with material balance data to estimate the TRU and ^{230} Th content of dust in the various work areas of the feed plant." He also notes that dust in the fluorination tower area may have had significantly different concentrations than he reported when it was rarely opened to access components. For the C-410 Operations tasks, except the ash receiver, the plutonium, neptunium, thorium and uranium fractions used in calculations are the same as Baker's. The radionuclide fractions for the pulverizer and ash receiver are based on a range of values identified in the Baker report [25], Oak Ridge Operations Task Force report on uranium recycle materials processing [88] (which references Fernald sampling data), and HP summary reports [60, 61]. Fractions for the converter salvage line and converter maintenance line are based on health physics inspection reports [57, 58].

Different chemical compounds of a given radionuclide clear from the lungs at different rates. This difference in clearance times results in different dose conversion factors for different chemical classes of a given radionuclide. The chemical forms of materials, and for uranium the percentage of enrichment, to which workers were exposed is an area of significant uncertainty. For the most part, this assessment uses the assumptions used by Baker in selecting chemical class (or type) of material. All chemical forms of neptunium are listed as Class W or Type M by the ICRP. Plutonium oxide is listed as Class Y or Type S by the ICRP. All other forms are assumed to be Class W or type M. It is assumed that plutonium exposures in these areas are primarily to Class W or type M materials. The ICRP lists thorium oxides and hydroxides as Class Y or Type S, and all other forms as Class W or Type M. It is assumed that thorium exposures in these areas are primarily to Class W or Type M.

Uranium, UF_6, UO_2F_2 and $UO_2(NO_3)_2$ are listed by the ICRP as Class D or Type F. UO_3, UF_4 and UCl_4 are listed as Class W or Type M. UO_2, U_3O_8 and other insoluble oxides are listed as Class Y or Type S. The following are assumptions and their bases for uranium chemical class assignment:

- The workers in the C-410 Control Room were exposed to UO_2F_2 fumes and UF_4 dusts. This assessment assumes, as Baker did, that the exposure in the C-410 Control Room was to 100% Class W uranium [25].

- It is assumed that uranium in the Green Salt Plant was Class W [25].

- The workers in the Cold Trap area were exposed to $U0_3$, UF_4 and occasionally to UO_2F_2. This assessment assumes, as Baker did, that the exposure in the Cold Trap area was to 100% Class W uranium [25].

- The workers in the Fluorination Tower area were exposed to UF_4 and UO_2F_2. Consistent with Baker, it is assumed that uranium in the Fluorination Tower area was 60% Class D and 40% Class W [25].

- Baker assumes that operators in the Powder Handling area were exposed to UO_3. This assessment assumes that insoluble oxides may also have been present in the Powder Handling area and assigns uranium exposures to 50% Class W and 50% Class Y.[25, 36]

- The Pulverizer area is assumed to have a uranium chemical source term that is similar to the Fluorination tower, and therefore uranium classes are designated as 60% Class D and 40% Class W [25].

- The uranium in the converter salvage and converter maintenance area is all assumed to be Class D material.

It should be noted that the above assumptions regarding chemical classification of the radionuclides are just that - assumptions. Exposures to the less soluble Class Y or Type S materials in certain areas of the plant are considered likely.

7.5.3 Worker exposure periods

The assumed number of hours of exposure for the following areas are similar to those reported by Baker for the C-400 Control Room, the Green Salt Plant, the Fluorination Tower, the Cold Trap and the Powder areas. Based on discussions with worker, slight (and subjective) modifications to these numbers were made. Discussions with workers were also the basis for exposure times on the pulverizer, the ash receiver, the converter salvage line, and in the converter maintenance area. The estimate of hours for the converter maintenance area was also supported by job/task analyses documented in Health Physics Inspection Reports [57, 58].

7.5.4 Estimating intake

The above assumptions regarding air sampling concentrations, radionuclides and their fractional contributions, and the number of hours exposed are used to calculate radionuclide-specific air concentrations. These air concentrations are then used with an assumed worker breathing rate of 1.2 cubic meter per hour to calculate intakes.

While there certainly is some statistical uncertainty in the presented data, it is not clear how to properly quantify this statistical uncertainty, because of the unavailability of the original calculations and calibrations of the collection and counting equipment. The numbers here are based on reported data that did not include background counting data, source counting data, calibration data or mention of uncertainty in the final reported numbers. Additionally, the purpose

of these calculations is to provide a starting place to determine if additional data is needed. These calculations should be considered preliminary.

Table 7.9 shows estimates of intakes for three worker scenarios. All scenarios are based on a worker being in an area or working on a task for the given number of hours per year and assumes no benefit from the use of respiratory protection. The different work scenarios are defined as follows:

- C-410/420 Operator who worked in the areas listed in the Tables,
- C-400 Operator who worked on Converter Salvage and the Pulverizer, and
- Converter Maintenance Mechanic who worked on converter maintenance during periods of elevated airborne radioactivity.

It should be noted that the above scenarios were chosen because of the available data for these areas. This does not mean that there were not other areas where transuranic materials were significant components of the radioactive source term. In fact, the *Phase II Independent Investigation of the Paducah Gaseous Diffusion Plant (Feb. 2000)* report identifies transuranics as a hazard in a number of other areas in the plant [2].

Table 7.9. Estimations of Air Concentrations and Intakes by Radionuclide for Selected Jobs/Areas

Pu-239	**Work Hours per Year**	**Average Alpha dpm/m^3**	**Fraction Pu-239**	**Average Pu-239 Air Concentration µCi/cc**	**Average Intake in a Year, dpm**	**Maximum Alpha dpm/m^3**	**Fraction Pu-239**	**Maximum Pu-239 Air Concentration µCi/cc**	**Maximum Intake in a Year, dpm**
Control Room, C-410	300	10	0.09	4.1E-13	324	50	0.09	2.0E-12	1620
Green Salt Plant, C-420	300	100	0.00033	1.5E-14	12	1300	0.00033	1.9E-13	154
Cold Trap	200	20	0.07	6.3E-13	336	100	0.07	3.2E-12	1680
Fluorination Tower, C-410	200	80	0.09	3.2E-12	1728	1000	0.09	4.1E-11	21600
Powder Handling, C-410, C-420	200	80	0.00033	1.2E-14	6	1300	0.00033	1.9E-13	103
Ash Receivers	75	117	0.15	7.9E-12	1580	1000	0.35	1.6E-10	31500
Pulverizer	50	75	0.15	5.1E-12	675	1200	0.35	1.9E-10	25200
Converter Salvage Line, C-400	50	28	1	1.3E-11	1680	161	1	7.3E-11	9660
Converter Maintenance	N.A.								
Np-237	**Work Hours per Year**	**Average Alpha dpm/m^3**	**Fraction Np-237**	**Average Np-237 Air Concentration µCi/cc**	**Average Intake in a Year, dpm**	**Maximum Alpha dpm/m^3**	**Fraction Np-237**	**Maximum Np-237 Air Concentration µCi/cc**	**Maximum Intake in a Year, dpm**
Control Room, C-410	300	10	0.007	3.2E-14	25	50	0.007	1.6E-13	126
Green Salt Plant, C-420	300	100	0.00018	8.1E-15	6	1300	0.00018	1.1E-13	84
Cold Trap	200	20	0.005	4.5E-14	24	100	0.005	2.3E-13	120
Fluorination Tower, C-410	200	80	0.007	2.5E-13	134	1000	0.007	3.2E-12	1680
Powder Handling, C-410, C-420	200	80	0.00018	6.5E-15	3	1300	0.00018	1.1E-13	56
Ash Receivers	75	117	0.007	3.7E-13	74	1000	0.01	4.5E-12	900
Pulverizer	50	75	0.007	2.4E-13	32	1200	0.01	5.4E-12	720
Converter Salvage Line, C-400	50	502	1	2.3E-10	30120	5787	1	2.6E-09	347220
Converter Maintenance	50	50	1	2.3E-11	3000	500	1	2.3E-10	30000

Th-230	Work Hours per Year	Average Alpha dpm/m^3	Fraction Th-230	Average Th-230 Air Concentration µCi/cc	Average Intake in a Year, dpm	Maximum Alpha dpm/m^3	Fraction Th-230	Maximum Th-230 Air Concentration µCi/cc	Maximum Intake in a Year, dpm
Control Room, C-410	300	10	0.025	1.1E-13	90	50	0.025	5.6E-13	450
Green Salt Plant, C-420	300	100	0.000028	1.3E-15	1	1300	0.000028	1.6E-14	13
Cold Trap	200	20	0.02	1.8E-13	96	100	0.02	9.0E-13	480
Fluorination Tower, C-410	200	80	0.025	9.0E-13	480	1000	0.025	1.1E-11	6000
Powder Handling, C-410, C-420	200	80	0.000028	1.0E-15	1	1300	0.000028	1.6E-14	9
Ash Receivers	75	117	0.143	7.5E-12	15060	1000	0.34	1.5E-10	30600
Pulverizer	50	75	0.143	4.8E-12	644	1200	0.34	1.8E-10	24480
Converter Salvage Line, C-400	50	58	1	2.6E-11	3480	602	1	2.7E-10	36120
Converter Maintenance	N.A.								
Uranium	**Work Hours per Year**	**Average Alpha dpm/m^3**	**Fraction Uranium**	**Average Uranium Air Concentration µCi/cc**	**Average Intake in a Year, dpm**	**Maximum Alpha dpm/m^3**	**Fraction Uranium**	**Maximum Uranium Air Concentration µCi/cc**	**Maximum Intake in a Year, dpm**
Control Room, C-410	300	10	0.878	4.0E-12	3161	50	0.878	2.0E-11	15804
Green Salt Plant, C-420	300	100	0.999462	4.5E-11	35981	1300	0.999462	5.9E-10	467748
Cold Trap	200	20	0.905	8.2E-12	4344	100	0.905	4.1E-11	21720
Fluorination Tower, C-410	200	80	0.878	3.2E-11	16858	1000	0.878	4.0E-10	210720
Powder Handling, C-410, C-420	200	80	0.999462	3.6E-11	19190	1300	0.999462	5.9E-10	311832
Ash Receivers	75	117	0.7	3.7E-11	7371	1000	0.3	1.4E-10	27000
Pulverizer	50	75	0.7	2.4E-11	3150	1200	0.3	1.6E-10	21600
Converter Salvage Line, C-400	50	554	1	2.5E-10	33240	3879	1	1.7E-09	232740
Converter Maintenance	50	50	1	2.3E-11	3000	500	1	2.3E-10	30000

7.5.5 Estimating doses

The estimated intakes were multiplied by the appropriate chemical class fractions, enrichment fractions and dose conversion factors in the EPA's Federal Guidance Report No. 11 (EPA-520/1-88-020, September 1988) to obtain the 50-year committed effective doses equivalent (CEDEs) and the 50-year committed doses equivalent (CDEs). The results are presented by radionuclide in Table 7.10. These results are summed in Table 7.11 to obtain the estimated total dose for the different areas and tasks. The dose conversion factors for this preliminary assessment are based on ICRP 30 methodology and assume a particle size of 1 µm Activity Median Aerodynamic Diameter (AMAD). It should be noted that Baker [25] assumed particle sizes of 4 and 10 µm AMAD in his Pu-239 and Np-237 dose calculations. A memo dated March 11, 1960 [49] noted that the transuranics materials at PGDP had a particle size of "0.5 µm, the very worst size, biologically speaking". No actual study of particle sizes at PGDP, including locations of measurement, measurement methodologies and results of measurements has been located. The Baker report was the only one reviewed that used particle sizes that differed from 1µm AMAD in dose calculations.

Based on worker transcripts, it is apparent that many individuals worked in these areas and/or tasks for time periods ranging up to 15 years. To estimate potential exposures for time periods other than

1 year, the results from Tables 7.10 and 7.11 can be multiplied by the appropriate number of years to obtain an estimate of the potential exposure.

Based on the above scenarios, it is seen from the Tables that the dose equivalent due to internally deposited radioactive materials may have resulted in some worker radiation exposures that approached or exceeded current regulatory limits**.** The Tables show that the average calculated CEDE values for a given job/area range from about 0.7 rem per year to about 8 rem per year. The maximum calculated CEDE values for a given job/area range from about 7 rem per year to about 100 rem per year. It should also be noted that a worker was not necessarily excluded from working in all three jobs/areas.

Because of the changing methods of calculating and regulating internal doses, it is not always clear how a limit in effect at given time should be applied. Because the doses equivalent calculated in Tables 7.10 and 7.11, are based on ICRP 30 methodology, it is reasonable to compare them to the limits in ICRP 30. Note that these are not regulatory limits that were in effect at the time of exposure, but current international standards on which 10 CFR 835 and 10 CFR 20 limits are based. The ICRP 30 limit, also referred to as the Total Effective Dose Equivalent (external dose plus committed internal dose), is 5 rem in a year which means that the CEDE (internal doses calculated in the tables above) should not exceed 5 rem in a year. The ICRP 30 limit for organs and tissues (e.g., lung and bone surfaces) is 50 rem in a year.

In summary, the doses equivalent calculated in this section are based on fixed-head air sampling results and assumptions regarding worker locations and stay-times. The results indicate that prior to 1980, some workers' doses may have approached or exceeded current regulatory limits. It should also be stressed that the calculated doses equivalent are preliminary estimates based on the currently available data.

Table 7.10. Estimations of annual hypothetical workers' doses for given jobs/areas by radionuclide

Pu-239		**Based on AVERAGE Air Concentrations**				**Based on MAXIMUM Air Concentrations**			
	Hours per Year	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE – rem**
Control Room, C-410	300	3.2E+02	6.3E-02	9.3E-03	1.1E+00	1.6E+03	3.1E-01	4.7E-02	5.7E+00
Green Salt Plant, C-420	300	1.2E+01	2.3E-03	3.4E-04	4.2E-02	1.5E+02	3.0E-02	4.5E-03	5.4E-01
Cold Trap	200	3.4E+02	6.5E-02	9.7E-03	1.2E+00	1.7E+03	3.2E-01	4.8E-02	5.9E+00
Fluorination Tower, C-410	200	1.7E+03	3.3E-01	5.0E-02	6.1E+00	2.2E+04	4.2E+00	6.2E-01	7.6E+01
Powder Handling, C-410, C-420	200	6.3E+00	1.2E-03	1.8E-04	2.2E-02	1.0E+02	2.0E-02	3.0E-03	3.6E-01
Ash Receivers	75	1.6E+03	3.1E-01	4.6E-02	5.6E+00	3.2E+04	6.1E+00	9.1E-01	1.1E+02
Total			**7.7E-01**	**1.1E-01**	**1.4E+01**		**1.1E+01**	**1.6E+00**	**2.0E+02**
Pulverizer	50	6.8E+02	1.3E-01	1.9E-02	2.4E+00	2.5E+04	4.9E+00	7.3E-01	8.9E+01
Converter Salvage Line, C-400	50	1.7E+03	3.2E-01	4.8E-02	5.9E+00	9.7E+03	1.9E+00	2.8E-01	3.4E+01
Total			**4.6E-01**	**2.8E-01**	**8.3E+00**		**6.7E+00**	**1.0E+00**	**1.2E+02**
Converter Maintenance	N.A.								
Np-237		**Based on AVERAGE Air Concentrations**				**Based on MAXIMUM Air Concentrations**			
	Hours per Year	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**
Control Room, C-410	300	2.5E+01	6.1E-03	6.8E-04	1.4E-01	1.3E+02	3.1E-02	3.4E-03	6.9E-01
Green Salt Plant, C-420	300	6.5E+00	1.6E-03	1.7E-04	3.5E-02	8.4E+01	2.0E-02	2.3E-03	4.6E-01
Cold Trap	200	2.4E+01	5.8E-03	6.4E-04	1.3E-01	1.2E+02	2.9E-02	3.2E-03	6.5E-01
Fluorination Tower, C-410	200	1.3E+02	3.3E-02	3.6E-03	7.3E-01	1.7E+03	4.1E-01	4.5E-02	9.2E+00
Powder Handling, C-410, C-420	200	3.5E+00	8.4E-04	9.3E-05	1.9E-02	5.6E+01	1.4E-02	1.5E-03	3.1E-01
Ash Receivers	75	7.4E+01	1.8E-02	2.0E-03	4.0E-01	9.0E+02	2.2E-01	2.4E-02	4.9E+00
Total			**6.5E-02**	**7.2E-03**	**1.5E+00**		**7.2E-01**	**8.0E-02**	**1.6E+01**
Pulverizer	50	3.2E+01	7.7E-03	8.5E-04	1.7E-01	7.2E+02	1.8E-01	1.9E-02	3.9E+00
Converter Salvage Line, C-400	50	3.0E+04	7.3E+00	8.1E-01	1.6E+02	3.5E+05	8.4E+01	9.3E+00	1.9E+03
Total			**7.3E+00**	**8.1E-01**	**1.6E+02**		**8.5E+01**	**9.3E+00**	**1.9E+03**
Converter Maintenance	**50**	3.0E+03	**7.3E-01**	**8.1E-02**	**1.6E+01**	3.0E+04	**7.3E+00**	**8.1E-01**	**1.6E+02**
Th-230		**Based on AVERAGE Air Concentrations**				**Based on MAXIMUM Air Concentrations**			
	Hours per Year	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**
Control Room, C-410	300	9.0E+01	1.3E-02	2.4E-03	3.2E-01	4.5E+02	6.6E-02	1.2E-02	1.6E+00
Green Salt Plant, C-420	300	1.0E+00	1.5E-04	2.7E-05	3.6E-03	1.3E+01	1.9E-03	3.5E-04	4.7E-02
Cold Trap	200	9.6E+01	1.4E-02	2.6E-03	3.5E-01	4.8E+02	7.0E-02	1.3E-02	1.7E+00
Fluorination Tower, C-410	200	4.8E+02	7.0E-02	1.3E-02	1.7E+00	6.0E+03	8.8E-01	1.6E-01	2.2E+01
Powder Handling, C-410, C-420	200	5.4E-01	7.9E-05	1.4E-05	1.9E-03	8.7E+00	1.3E-03	2.3E-04	3.1E-02
Ash Receivers	75	1.5E+03	2.2E-01	4.0E-02	5.4E+00	3.1E+04	4.5E+00	8.2E-01	1.1E+02
Total			**3.2E-01**	**5.8E-02**	**7.8E+00**		**5.5E+00**	**1.0E+00**	**1.4E+02**
Pulverizer	50	6.4E+02	9.4E-02	1.7E-02	2.3E+00	2.4E+04	3.6E+00	6.6E-01	8.8E+01
Converter Salvage Line, C-400	50	3.5E+03	5.1E-01	9.3E-02	1.3E+01	3.6E+04	5.3E+00	9.7E-01	1.3E+02
Total			**6.0E-01**	**2.2E-01**	**1.5E+01**		**8.9E+00**	**1.6E+00**	**2.2E+02**
Converter Maintenance	N.A.								
Uranium		**Based on AVERAGE Air Concentrations**				**Based on MAXIMUM Air Concentrations**			
	Hours per Year	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**	**Intake dpm**	**CEDE rem**	**Lung CDE rem**	**Bone Surface CDE - rem**
Control Room, C-410	300	3.2E+03	1.1E-02	9.5E-02	1.6E-02	1.6E+04	5.3E-02	4.8E-01	8.2E-02
Green Salt Plant, C-420	300	3.6E+04	1.2E-01	1.1E+00	1.9E-01	4.7E+05	1.6E+00	1.4E+01	2.4E+00
Cold Trap	200	4.3E+03	1.5E-02	1.3E-01	2.3E-02	2.2E+04	7.3E-02	6.6E-01	1.1E-01
Fluorination Tower, C-410	200	1.7E+04	3.4E-02	2.1E-01	8.8E-02	2.1E+05	4.3E-01	2.6E+00	1.1E+00
Powder Handling, C-410, C-420	200	1.9E+04	5.7E-01	5.7E+00	1.0E-01	3.1E+05	9.3E+00	9.3E+01	1.6E+00
Ash Receivers	75	7.4E+03	1.5E-02	9.2E-02	3.8E-02	2.7E+04	5.5E-02	3.4E-01	1.4E-01
Total			**7.7E-01**	**7.3E+00**	**4.5E-01**		**1.2E+01**	**1.1E+02**	**5.5E+00**
Pulverizer	50	3.2E+03	6.4E-03	3.9E-02	1.6E-02	2.2E+04	4.4E-02	2.7E-01	1.1E-01
Converter Salvage Line, C-400	50	3.3E+04	3.9E-02	2.0E-02	1.7E-01	2.3E+05	2.7E-01	1.4E-01	1.2E+00
Total			**4.5E-02**	**5.9E-02**	**1.9E-01**		**3.2E-01**	**4.1E-01**	**1.3E+00**
Converter Maintenance	**50**	3.0E+03	**3.5E-03**	**1.8E-03**	**1.6E-02**	3.0E+04	**3.5E-02**	**1.8E-02**	**1.6E-01**

Table 7.11. Estimated hypothetical workers' annual doses for selected areas/jobs based on air sampling results

Assumption:
Material is assumed to be a mixture of class W Pu-239, class W Np-237, class W Th-230 and a mixture of classes D and W natural uranium

Worker and Area or Job	Hours per year	Based on AVERAGE Air Concentrations			Based on MAXIMUM Air Concentrations		
		CEDE rem	Lung CDE rem	Bone Surface CDE rem	CEDE rem	Lung CDE rem	Bone Surface CDE rem
C-410/420 Operator							
Control Room, C-410	300	0.093	0.11	1.6	0.46	0.54	8.1
Green Salt Plant, C-420	300	0.12	1.1	0.27	1.6	14	3.5
Cold Trap	200	0.099	0.14	1.7	0.50	0.72	8.4
Fluorination Tower, C-410	200	0.47	0.28	8.6	5.9	3.4	108
Powder Handling, C-410, C-420	200	0.58	5.7	0.14	9.4	93	2.3
Ash Receivers	75	0.56	0.18	11	11	2.1	226
Total	**1275**	**1.9**	**7.5**	**24**	**29**	**113**	**356**
C-400 Operator							
Pulverizer	50	0.24	0.077	4.9	8.7	1.7	181
Converter Salvage Line, C-400	50	8.2	0.97	183	92	11	2058
Total	**100**	**8.4**	**1.0**	**188**	**101**	**12**	**2238**
Converter Maintenance Mechanic							
Converter Maintenance (during period of elevated airborne radioactivity)	**50**	**0.73**	**0.08**	**16**	**7.3**	**0.82**	**164**

7.5.6 Fission Products

Internal doses from fission products, such as technetium-99, will tend to be significantly lower than internal doses from the radionuclides noted in section 7.5.3. The reason for this is two-fold. The fractional activity in the airborne material will tend to be lower than the fractional activity of uranium, thorium or the transuranic material, depending on the process. And the dose conversion factors generally will be smaller.

For workers in the feed plant, Baker [25] estimates an annual deposition of technetium-99 in the pulmonary region of the lung to be no more than 1000 dpm. Dividing this intake by the deposition fraction of 0.25 results in an annual intake of 4000 dpm. The intake is multiplied by the appropriate dose conversion factor in the EPA's Federal Guidance Report No. 11 (EPA-520/1-88-020, September 1988) to obtain the 50-year committed effective doses equivalent (CEDEs). The more conservative Class W conversion factor, 2.25E-9 Sv/Bq (1.35E-5 Rem/dpm), is chosen to provide the more conservative estimate of dose. The resulting annual dose estimate is 0.02 mrem. It is suspected that doses may have been higher during technetium-99 recovery operations conducted in buildings C-710 and C-400.

A number or reports indicate that internal doses at PGDP from fission products are not significant compared to the internal doses from the alpha emitting radionuclides; however, no quantitative information was found regarding fission product concentrations in air or dust at PGDP. It should be noted that there are areas in the feed plant and in the cascade where fission products reportedly concentrate. While it is expected that these materials pose more of an external radiation hazard than an internal radiation hazard, a more quantitative assessment would better answer this question.

7.5.7 New ICRP Models

In the last decade, new criteria and models for controlling and calculating internal doses have been developed and adopted by the International Committee on Radiation Protection (ICRP). In particular, new values for weighting organ doses have been defined in ICRP 60. A new lung model has been developed that provides a more realistic basis for radioactivity retention and excretion that can be modified to specifically address different breathing patterns, and allows knowledge of the dissolution and absorption behavior of different materials in the lung to be used in assessments. Also, new metabolic models that are believed to more realistically model material behavior in the body and that address systemic excretion have been set forth in ICRP 67 and ICRP 69. For the interested reader, dose calculation results for the intakes presented in Table 7.9 are presented in Appendix G using these new models which are calculated with dose conversion factors from ICRP 68 for particle sizes of 1µm and 5µm AMAD.

7.6 Combining Internal and External Doses for a Selected Group of Workers

At this time the available data is not robust enough to estimate the total internal plus external dose for an average worker or a maximally exposed worker at the PGDP. However, an attempt is made to estimate an average and a high dose to a group of workers believed to have received higher

transuranic exposures as described in Section 7.5. The Health Physics Summary Reports [89] include limited data regarding maximum and average external doses for these workers. The data is reported as average and maximum milliroentgen per week in nine monthly reports dated from June 1956 to March 1959 and was reported as milliroentgen per month in reports dated from August 1959 to November 1963 for workers listed in C-410 operations, C-410 maintenance, or department 5751. The arithmetic mean of the reported average monthly values and maximum monthly values for C-410 operations and maintenance were determined to be approximately 40 milliroentgen per month and 550 milliroentgen per month respectively. For the estimates provided in this section it is assumed that one roentgen equals one rem.

The estimates above are converted to annual exposure estimates by multiplying the monthly values by twelve. Based on these estimates it is estimated that the C-410 operations and maintenance workers could have received an average external dose of 0.48 rem/year and a maximum of 6.6 rem/year.

Because workers were reportedly rotated through jobs at unspecified intervals, this may be an overestimate of potential external doses. Total estimated doses for these tasks and areas can then be approximated by adding the internal doses listed in Table 7.11 to the external doses noted above. For the C-410 operators and maintenance workers, the total annual doses are estimated as ranging from 1.68 rem/year (1.2 (internal) + 0.48 (external)) to 35.6 rem/yr (29 (internal) + 6.6 (external)).

Additionally, a simplistic calculation provides a rough estimate of total organ radiation doses by adding the external exposure to the internal organ dose.

8.0 EXPOSURE ASSESSMENT UNCERTAINTIES

This was an "Exposure Assessment" not an "Exposure Reconstruction". As such, there are many possible sources of errors and uncertainties. Virtually all of the data that were used in this study were not obtained from the original, hard copy records. Only a very small sample of the derived data was actually checked against some of the original records, and discrepancies were found. Therefore, none of the data should be considered as "validated" or "verified" and the conclusions drawn from the derived data must also be considered as preliminary. The dosimetric values or ranges reported are for the purposes of comparing worker groups, departments and workplace sites for their relative potential for worker radiation exposure. These data should not be used to create or approximate individual worker radiation dose estimates.

A QA/QC check of the worker radiation exposure electronic databases with the original, hard copy records is recommended. This QA/QC check should identify the implications of this new information to the relative ranking of the potential for increased radiation exposure to workers and conclusions of this report.

There were a number of sources of possible "missed doses". Some of these include:

- A lack of documentation. This would include doses that may have never been recorded, may have been discarded, or records that the current Team could not locate or otherwise did not obtain. Examples include:

  - Early Health Physics and Hygiene reports indicate some limited *in vitro* bioassay monitoring for neptunium, thorium and plutonium exposures as early as 1959 [10] however, the provided database contained no urinalysis results for these isotopes prior to 1989.

  - Workers reported that elevated results from film badges were often discarded as invalid and not recorded in the individuals dose record. [33]

  - One incident report of a release, which occurred in C-720 in 1986, indicated that several individuals received significant exposures the two highest urine samples listed as 13 mg U/l and 5 mg U/l. The elevated urine samples were not in the database. [45]

  - A January 1953 report discusses an incident on 1/8/53 where 8 Union Carbide workers were exposed; all with positive urine samples averaging 0.457 mg U/liter. For that date (1/8/53) the database contained 17 samples; averaging the highest 8 samples yielded an average of 0.315 mg U/liter. This indicates that some elevated data are missing. [46]

- A failure to monitor the exposure. There are numerous examples during the history of the plant where the potential for radiological exposure may have existed, but was not monitored, or perhaps inadequately monitored. Examples include:

- From 1952 through 1960 approximately 200-500 workers were monitored for external radiation exposure. In 1961 the program was broadened and approximately 1700 workers were monitored. The increase in the number of workers monitored was not a result of an increase in the plant workforce during this time but rather a change in the health physics program philosophy [34]. Exposures to these additional work groups would have been missed for the early years of plant operations.

- Interviews and documents indicated that in the early 1950s a decision was made that extremity monitoring was not required because it was felt that these doses were not likely to exceed 2.5 times the whole-body exposure. The Phase II reports states that "whole-body exposures to operators and the dose rates in the ash receiver area were large enough that they could exceed 10 percent of the extremity limit and, therefore, would necessitate extremity monitoring. Similarly, extremity monitoring should have been done for shell and crucible cleaning operations in the metals building (C-340)." [2]

- Health Physics survey and inspection reports identify several areas of increased concentrations of TRU (identified as high as 90 percent in one area) [60]. Further, the DOE Phase II report states "They (PGDP Health Physics Staff) knew that traditional uranium controls would not be sufficient for areas where neptunium would concentrate …". This suggests that the use of uranium urinalysis as a means of controlling exposure to transuranics would not have been effective.

- The failure to recognize an opportunity for a radiological exposure. Again there are examples where the potential for radiological exposure may not have been recognized or fully appreciated. For example:

  - The Health Physics and Hygiene Department assumed that nearly all uranium ingested or inhaled was soluble and quickly excreted from the body without harm or long-term effects. In fact, aerosols of insoluble uranium compounds were generated in some work areas, such as in the feed plant, and by maintenance activities, such as grinding, buffing, and welding. Insoluble forms of uranium were also present in the Metals building (C-340). [2]

  - It was reported that over time, buildings were used for different purposes and the potential for worker radiation exposure in those buildings may not have been recognized. [33]

- The lack of sensitivity of the monitoring or assay techniques. For example:

  A 1990 preliminary evaluation of the mobile whole body counter notes, "the counter's capability for analysis of the above-referenced radionuclides [uranium, neptunium, plutonium and americium] with the exception of U-235, is somewhat questionable."[90]

9.0 FEASIBILITY OF FUTURE BIOASSAY/RADIOASSAY PROGRAMS

Synopsis *¾ The Team was directed to review the modern methods for exposure assessment, confirmation and dose reconstruction. In the event that such information is needed, a variety of techniques and tools are available to assess past exposures. Bioassay approaches include sensitive methods for the detection of some radionuclides in tissues and body fluids. These include, for example, fission track analysis (FTA), accelerator mass spectroscopy (AMS), thermal ionization mass spectroscopy (TIMS) and inductively coupled plasma mass spectroscopy (ICP-MS). Some whole body/organ counting methods are being developed that may also detect low levels of some of the uranium daughters and some other radionuclides in the body. The technique of electron paramagnetic resonance (EPR) has also been used to reconstruct lifetime external radiation exposures using dental enamel. Fluorescence-in-situ-hybridization (FISH, also called "chromosome painting") is an emerging technology to assess biological damage from radiation at the level of the chromosome. These techniques are available, but their use depends, of course, on the information being sought or the question being addressed and a thorough consideration of their limitations. To estimate lifetime doses for individuals it would be advisable to consider each individual's exposure history.*

It is also feasible to conduct radioassay techniques to determine with greater certainty the isotope composition of residual materials at the plant. While modern tools and techniques are available to do this, this need and the suitability of the materials would need to be established.

9.1 Bioassay Techniques in Dosimetry

Table 9.1 summarizes some of the retrospective techniques, their applications, and optimal minimum detectable activities or dose. These techniques have and are being used in populations, other than Paducah to quantify exposures from environmental and occupational sources. The detection limits of these techniques, if appropriately applied, are sufficiently sensitive that in many cases, those individuals who had received elevated external exposures or had elevated body levels of plutonium could be identified. Techniques are not available, however, for all conceivable types of past exposures that may have occurred at Paducah. Many of these techniques are better predictors of "group" dose rather than dose to individuals. Additionally, there are limitations to all of these techniques as discussed below. A contemporary discussion of retrospective techniques, their applications and sensitivities, and their associated limitations can be found in Jacob et al. (62) and Straume et al (63).

Table 9.1 Summary of some bio-dosimetry and measurement techniques used to measure or estimate past exposure levels to external radiation or current body concentrations of internal emitters.

Technique	Application	Minimum detectable activity or dose*	Reference
Fission track analysis	Pu in biological tissues or fluids	~100 aCi**	64, 65, 66
Accelerator or Thermal Ionization mass spectroscopy, and Inductively Coupled Plasma Mass Spectroscopy	Pu in biological tissues or fluids	~100 aCi	67, 68, 69
EPR	External ß, (	~3-10 Rem	70
FISH	External dose and some internal doses	~20 Rem	71
Luminescence	External (	~5 Rem	72

* Under well-controlled experimental situations but data vary between different laboratories and studies.
** aCi: attoCurie = 10^{-18} Ci.

9.1.1 Fission track analysis, accelerator and thermal ionization mass spectroscopy.

The usual method that is employed to determine potential plutonium exposure is to measure the amount of the nuclide of interest in excreta (urine and/or feces) and then estimate the current total body content. From this information, models are employed (e.g. ICRP models) to estimate the radiation doses to the tissues and organs over time. These models have many assumptions and often must be adapted to the characteristics of the populations or individuals for which they are applied. Thus, there may be substantial uncertainties in the retrospective doses that are calculated using these various models. There are a variety of chemical and physical methods that may be used to measure the various types of nuclides that may be of interest. The methods to measure plutonium that might be considered include fission track analysis (FTA), Accelerator Mass Spectroscopy (AMS) or the related techniques of Thermal Ionization Mass Spectroscopy (TIMS), and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS).

Fission track analysis has been used to determine the levels of plutonium in excreta for some populations. These include residents in the Marshall Islands [73,74], in northern and southern Utah [75], surrounding Rocky Flats [76], and the Nevada test site [64]. Some of the limitations for FTA include complex chemical separations to eliminate ^{235}U which will mask some of the plutonium measurements and that few laboratories currently are capable of conducting this analysis.

Mass spectroscopy is also being used to determine plutonium in biological tissues. For example, the Los Alamos National Laboratory uses this technology as part of their routine health physics program. Mass spectroscopy has been used to determine the plutonium ratios in water surrounding

French Polynesia [67] and in populations in Ireland [68]. This technique is limited by the chemical separation of uranium and similar to FTA are performed by relatively few laboratories.

9.1.2 Electron paramagnetic resonance to measure total external radiation exposure

Electron paramagnetic resonance (EPR), formerly known as 'electron spin resonance' (ESR) is a technique that is used to measure trapped electron populations in a crystal generated by exposure to ionizing radiation. For human application, this involves the analysis of tooth enamel. When EPR was applied to a large population, the method was deemed to be successful in reconstructing external exposures and international comparisons have been made [77,78] that include former nuclear workers [79], atomic bomb survivors [80], exposed civilian populations [81] and for various radiological workers [82]. The radiation-induced signals that are present in tooth enamel (or bone) are stable over long periods of time. Jacob et al. [62] indicate in their review that the practical lower detection range is about 10 rad with a 95% confidence interval at these lower levels of about ± 100 percent. The problems with this approach are mostly practical: locating suitable materials and costs. Additionally, medical and dental x-rays and ultraviolet radiation will be recorded in the tooth enamel as a radiation exposure and would need to be subtracted to obtain environmental exposures. In some situations, the geometry of the detector (enamel) should be considered.

9.1.3 Fluorescence *In-Situ* Hybridization (FISH)

Chromosome aberrations as a result of radiation exposures have been measured in humans for many years. Chromosome dicentrics and translocations have been used as indicators of radiation exposure. Dicentrics in peripheral blood lymphocytes will decrease with time after exposure, but translocations are considered to be more stable. The frequency of dicentric aberrations in peripheral blood lymphocytes has been shown to correlate with acute whole body external radiation exposures [62]. Internal radiation exposures from radionuclides that distribute rather uniformly throughout the body (e.g. tritium, cesium) can be measured with FISH, however, radionuclides which localize in the body (e.g. plutonium in bone) may not be good candidates for FISH. Most worker populations are exposed chronically to lower doses of radiation and thus the detection of stable translocations was explored as a possible indicator of exposure. Fluorescence *in-situ* hybridization was developed to detect stable translocations and recent data suggests that the frequency of translocations following an exposure may be essentially constant for the life of the individual. Thus it may be possible to determine external and some internal radiation exposures regardless of the length of time after exposure [63,83].

The limitations of FISH include the inability to determine the non-uniformity in exposures with time in the individual worker and some investigators have cautioned that the technology needs additional validation prior to widespread use. Since some chemical exposures also produce chromosomal aberrations, knowledge of a worker's past exposure to these chemicals would need to be taken into consideration. Some investigators have also suggested that translocations with time after exposure in some individuals may not be stable [84]. Other considerations include obtaining the specimens and the associated expenses.

9.1.4 Luminescence

Luminescence measurements that include thermoluminescence (TL) and optically stimulated luminescence (OSL) are useful to measure the cumulative absorbed radiation dose in non-biological specimens that contain crystalline materials. By measuring the absorbed doses in materials such as bricks and using appropriate assumptions and models, exposures to populations who may have lived or worked in the location can be estimated after the subtraction of the natural background radiation. For example, TL and OSL measurements have been used in the reconstruction of doses received by individuals after the Chernobyl accident [85], in U.S. populations downwind from the Nevada Test Site [86] and from the atomic bomb in Hiroshima [87]. The limitations for an industrial site include the identification of suitable materials at locations where external radiation fields may have existed, and assumptions on occupancy and location of the workers relative to the radiation source.

9.1.5 Whole body counting techniques

The Team has also had some discussions with scientists concerning the feasibility of whole body counting methods to assess internal body burdens from uranium daughters and some other radionuclides. These discussions are in the preliminary stage but we expect such proposals would be available for administrative and scientific evaluation if the decision is made to implement such a program.

9.2 Radioassays of Residual Materials

The Team was charged with evaluating the feasibility of conducting new radioassays on residual materials. In the event that useful materials were identified, new assays may prove to be useful to determine the isotopic concentrations in these materials. There does remain considerable uncertainty on the isotopic concentrations identified in many historic records. Thus additional assessments may be of some benefit. Any new information would be compared against historical records and plant process information and may provide new information on potential worker exposures. For potential external exposures, methods exist to assess total external radiation doses to building materials, providing a foundation for worker dose reconstruction.

The Team did receive some information on the historic isotopic identity and concentrations of various samples taken at various times. Some of these documents were incomplete and the methods and/or units not described. Thus, doing new assays using modern methods subjected to stringent quality control procedures remains an attractive approach, providing that suitable test materials are identified.

10.0 EXPOSURE ASSESSMENT TEAM'S RECOMMENDATIONS FOR CONTINUED RESOLUTION OF EXPOSURE ISSUES AT THE PADUCAH GASEOUS DIFFUSION PLANT (PGDP)

The Team particularly encourages a verification of the electronic database against the original, hard copy dosimetry records (a quality control, QC, evaluation). This verification of both the accuracy and the completeness of the database are essential prior to any attempt to further assess individual worker exposures. A QA/QC check of the worker radiation exposure electronic databases at Paducah is recommended. This QA/QC check should address the above issues and their implications to the relative ranking of the potential for increased radiation exposure to workers and conclusions of this report.

Internal dose estimates based on available air sampling results and assumptions regarding radionuclide fractions and solubility are presented in this report. To ascertain that these calculations are reasonable, it is recommended that available pre-1989 transuranic and thorium bioassay monitoring records be obtained and, depending on the adequacy of the data, doses be calculated.

Further, the Team notes that there have been many advances in retrospective dosimetry that may be useful in determining past worker radiation exposures. Some bioassay programs have been implemented in the past at Paducah and such programs remain feasible to more accurately assess some internal doses. Some of the advancements in bioassay techniques include, but are not limited to, fission track analysis (FTA), thermal ionization mass spectroscopy (TIMS) and inductively coupled plasma mass spectroscopy (ICP-MS), or, whole body counting techniques, molecular methods such as fluorescence *in situ* hybridization (FISH) and electron paramagnetic resonance (EPR) methods using tooth enamel for estimating total body lifetime external exposures. The team recommends that a feasibility study of these techniques, including an assessment of the current capabilities and the applicability of these methods for purposes of retrospective dose assessment at the PGDP site, be conducted. The strengths and limitations of these techniques must be considered prior to their application and use for any future exposure assessment and/or dose reconstruction.

11.0 CONCLUSIONS

This exposure assessment was conducted to review, evaluate and summarize the historical radiological issues at the Paducah Gaseous Diffusion Plant that may have resulted in or had the potential for worker radiation exposures. While all types of radiation sources and exposures were considered, emphasis was placed on potential exposures to the transuranics, especially neptunium and plutonium. Neptunium and plutonium were present in trace amounts in some of the feed materials, but were concentrated during certain processes.

The Team used readily available documentation, transcripts of worker interviews and dosimetry and exposure records contained in an unverified electronic database. Using this information, the Team assessed the relative potential for radiation exposures to the different worker departments based on jobs, tasks, and work locations at the plant. There are a number of caveats and limitations to the conclusions made by the Team and the data presented should not be used to infer exposures that may have occurred to individuals. This would require a much more extensive dose reconstruction effort. The data presented should not be used to infer exposures that may have occurred to individuals, as much of the data came from unverified sources, the Team strongly urges caution in its use and interpretation with out a much more extensive dose reconstruction effort.

A QA/QC check of the worker radiation exposure electronic databases at Paducah is recommended. This QA/QC check should address the above issues and their implications regarding the relative ranking of the potential for increased radiation exposure to workers and conclusions of this report.

The Team estimates that 2,500 to 4,000 workers worked in areas with increased potential for internal and external radiation exposures. The Team estimates that approximately 200 workers received in excess of 1 rem in a calendar year, and also estimates that on the order of 10% of the 2,500 to 4,000 workers had the potential for internal exposures that may have approached or exceeded regulatory limits. The areas identified at increased potential for radiation exposures for both external and internal sources included the Feed Plant (C-410/420), Decontamination Building (C-400), Metals Building (C-340), and the Cascade Buildings (C-331, C-333, C-335, and C-337). Departments identified as having increased potential for worker radiation exposure included: process operators, chemical operators, maintenance mechanics, instrument mechanics, and electricians. Some of the tasks with increased potential for elevated worker radiation exposures included handling the ash, cleaning the cylinder heels, processing the derbies, pulverizer operations, flange grinding, changing the baghouse filters, and maintenance and repair of the fluorination towers, hydrogenation towers and cascade equipment.

It is likely that some or perhaps many worker radiation doses are not in the record. These "missed doses" could be due to a number of factors including, but not limited to, the lack of documentation, failure to adequately monitor the exposure, lack of sensitivity of the technique to assess smaller doses, or failure to recognize the potential for worker radiation exposure. The Team identified issues associated with the sensitivity of some of the historical methods. The Team also identified some original exposure data that was either inconsistent with or not included in the unverified

electronic database. The Team strongly recommends a review of the records in the database against the original records.

New radioassays of existing or legacy materials remains a viable option to further define the isotopic concentrations of materials that workers may have been exposed to. Likewise, existing and emerging technologies exist with the potential to better define the amounts of some radionuclides in potentially exposed workers and to thus predict radiation exposures, retrospectively.

12.0 ENDNOTES

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APPENDIX A

Composition of the Exposure Assessment Team

Composition of the Exposure Assessment Team:

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APPENDIX B

Abbreviations and Acronyms

AEC: United States Atomic Energy Commission

AIHI: American Industrial Hygiene Association

ALARA: as low as reasonably achievable

AMAD: Activity Median Aerodynamic Diameter

AMS: Accelerator Mass Spectroscopy

ANSI: American National Standards Institute

CDE: committed dose equivalent

CEDE: committed effective dose equivalent

CFM: cubic feet per minute

Ci: curies

CINDY: Code for Internal Dosimetry

CIP/CUP: cascade improvement/upgrade programs

cpm: counts per minute

CPS: Creative Pollution Solutions, Inc.

DOE: (United States) Department of Energy

dpm: disintegrations per minute

E: Effective Dose

EPR: electron paramagnetic resonance

ERDA: (United States) Energy Resource and Development Administration

ERT: enriched reactor tails

FISH: fluorescence-in-situ-hybridization (chromosome painting)

FMPC: Feed Materials Production Center (Fernald, Ohio)

FTA: Fission Track Analysis

Gy: Gray

^{3}H: tritium

H_t: Equivalent Dose

HF: hydrogen fluoride or hydrofluoric acid

HP: Health Physics

HTO: tritium oxide

ICP-MS: Inductively Coupled Plasma Mass Spectroscopy

ICRP: International Commission on Radiological Protection

IT: International Technology (as in "IT" Corporation)

LET: linear energy transfer

LLNL: Lawrence Livermore National Laboratory

MPC: maximum permissible concentration

MPD: maximum permissible dose

NBS: (United States) National Bureau of Standards (now the National Institute of Standards and Technology)

NCRP: National Council on Radiation Protection and Measurements

Np: neptunium

NpF_6: neptunium hexafluoride

ORAU: Oak Ridge Associated Universities

ORGPD: Oak Ridge Gaseous Diffusion Plant

OSL: Optically Stimulated Luminescence

PACE: Paper, Allied-Industrial, Chemical and Energy International Union

PGDP: Paducah Gaseous Diffusion Plant

ppb: parts per billion

ppm: parts per million

Pu: plutonium

PuF_6: plutonium hexafluoride

QA: Quality Assurance

QC: Quality Control

QF: Quality Factor

R: roentgens

RBE: relative biological effectiveness

RT: reactor tails

SI: International System of Units

Sv: Sievert

Tc: technetium

Team: The Exposure Assessment Team (for this report)

TEDE: Total Effective Dose Equivalent

Th: thorium

TIMS: Thermal Ionization Mass Spectroscopy

TL: thermoluminescence

TLD: thermoluminescence dosimeter

TRU: Transuranium elements (transuranics)

U: uranium

UF_4: uranium tetrafluoride

UF_6: uranium hexafluoride

UO_3: uranium oxide

USDOE: United States Department of Energy

USEC: United States Energy Corporation

APPENDIX C

Plant Processes, Facilities, and Buildings

Building Summary:

Building Number	Description
C-100	Administration
C-310	Product Withdrawal (Purge and Product building)
C-315	Tails withdrawal (Surge and waste building)
C-331	Cascade Process
C-333	Cascade Process
C-335	Cascade Process
C-337	Cascade Process
C-340	Uranium Metals Building (Reduction and Metals Facility)
C-360	Shipping building
C-400	Decontamination (cleaning) building
C-409	Stabilization building
C-410	Feed Plant
C-420	Oxide Conversion Plant (Greensalt Plant)
C-710	Technical Services building
C-720	Maintenance building
C-746B	South Warehouse
C-749	Uranium Scrap Burial Yard

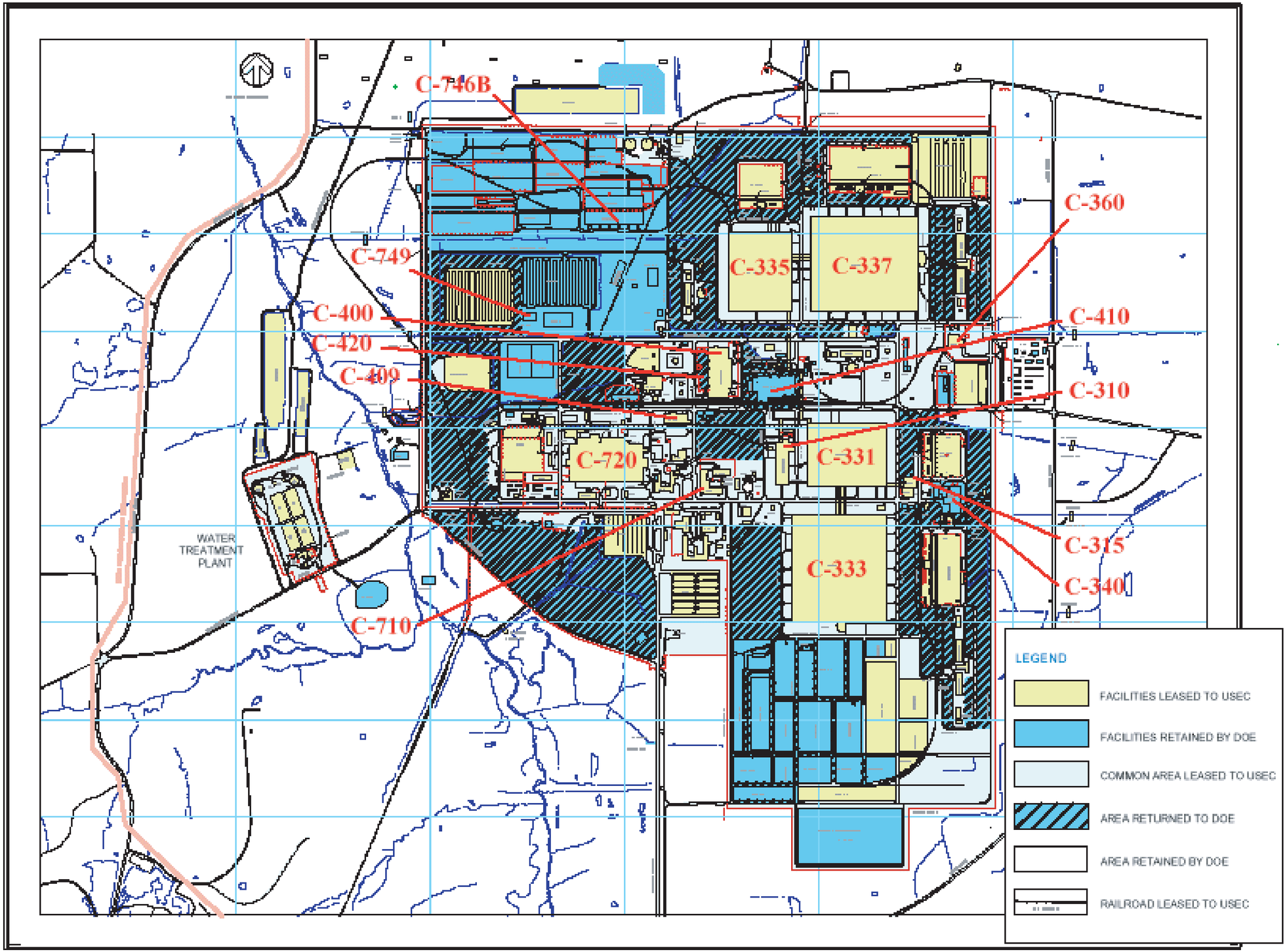

Figure C-1. Schematic drawing of approximate locations of PGDP buildings of interest in this report.

C-331, C-333, C-335, C-337 Cascade Process Buildings

These multi-story buildings contained approximately 2,000 cascade stages that are used to enrich ^{235}U contained in the UF_6 feed material. It was generally hot and noisy and there were periodic releases of UF_6 [CD005].

The basic component of a cascade cell was a single converter (Fig. C-2). It consisted of a cylindrical tank (2 sizes) with an input line and two output lines. The enriched output line contained a product that had a slightly greater content of ^{235}U than the input line, while the depleted output line had a slightly lower concentration. By hooking a series of converters together, it was possible to get an output containing about 3% ^{235}U compared to about 0.5% ^{235}U starter material.

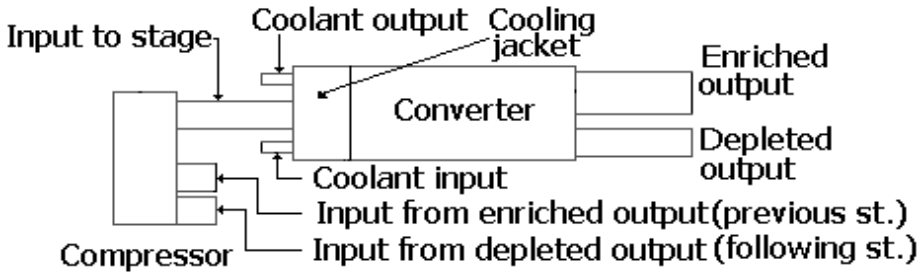

Figure C-2. Schematic layout of a cascade converter or cell with associated compressor. The control valves are not shown.

The front end of the converter consisted of a cooling jacket composed of coils through which cooling gas (freon) was continuously fed to reduce the temperature of the UF_6 prior to entering the converter proper. The working component of the converter was a porous, nickel tube through which ^{235}U would diffuse slightly faster than could ^{238}U.

UF_6 at room temperature is a solid. It sublimates at 53° C to form a gas. Heat is required to keep it in a gaseous state. The pressure of the UF_6 gas was increased prior to entry into the converter by a large compressor. This compressor had two input lines and one output line. The output line went directly to the converter. One of the input lines contained enriched output from the previous converter. The other input line contained depleted output from the next converter in the series. This pipe had a diameter of 42 inches and was large enough to crawl in.

Not shown in the figure are a number of shutoff valves that were used to control flow into and out of the converter. The compressor was connected to the lines by welded flange joints. On long lines, there were access holes (one reference stated "cut a hole in the side of the pipe") that could be opened to allow worker access. Access could also be achieved by removing sections of pipe. *The enrichment process was done by arranging several hundred converters into a cascade. Fig. 2 is a simplified drawing of a five unit cascade. Note that the depleted output of each cascade reenters the system through one of the input pipes of the compressor of the previous converter. The Paducah Plant had several thousand converters housed in four buildings, C-331, C-333, C-335 and C-337. Product withdrawal was done in Building C-310 while tails withdrawal occurred in*

Building 315. Major fires occurred in Buildings C-337, C-310 and C-315.

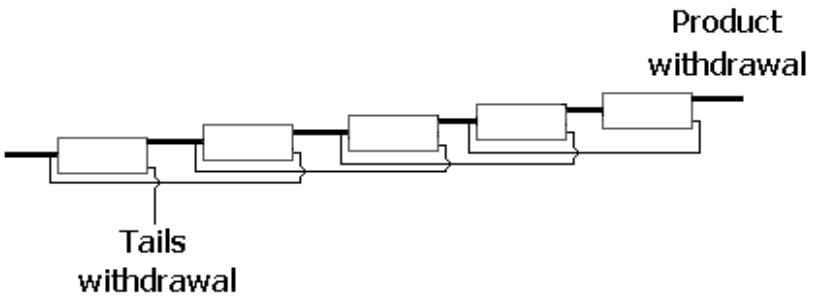

Figure C-3. Schematic layout of a cascade consisting of 5 converters.

The workforce within the process buildings was: operators (9/shift), maintenance mechanics (10-15/shift), electricians (8/shift), instrumentation mechanics (8/shift), janitor (1/shift), foremen (4/shift) [CD005]. From 1954 to present, there were generally 3 shifts per day.

C-400 Decontamination Building

Building C-400 is a five story building used for equipment decontamination, uranium recovery, powder pulverization, cylinder heels cleaning and neptunium recovery. The building was divided into halves by a partial partition.

Both small and large parts were decontaminated. Small parts were cleaned mechanically combined with weak nitric acid or potash solutions. Large parts were cleaned in large spray booths using spraying solutions. In addition, there were large containers of trichloroethylene for soaking.

The pulverizer was a five story stack type structure located in the far northeast corner of C-400. There was an opening at the top into which 55 gallon drums were emptied. The material was in the form of lumps and crushing was not involved. The drums themselves were picked up with a forklift and put on a conveyer belt (bucket elevator) where the lids were taken off. They were then run to the top of the pulverizer where they were dumped into a hopper. From there they went into a feeder and a series of shakers where the material was pulverized. The pulverizer contained a jaw crusher that would reduce the size of the particles. The operation also involved a screening process to obtain the correct sized particles. The product was dumped into large gray hoppers with dimensions of about 5' x 5' square x 6' tall which had a capacity of 7 tons. They usually processed about 12 drums a shift.

Cylinder heel cleaning involved rinsing the cylinders out with a solution that was then treated to cause precipitation of sludge. The liquid was disposed of via drainage ditches while the sludge was loaded into barrels and stored.

The spray booth wash solutions were treated to recover uranium. For a number of years, there were a neptunium and technetium recovery operations in C-400.

It appears that there were 2 or 3 operators/shift each manning the spray booths and the pulverizer.

The jobs in the decontamination building were done in rotation to divide the radiation exposure among the workers.

C-720 Maintenance Building

This building contained the shops including those for the machinists, maintenance mechanics, instrument mechanics, sheet metal workers, electricians, inspection workers, stores workers and janitors. The primary structure of interest from the standpoint of radiation safety was the compressor disassembly area. This was located in a pit at one end of the building and was several stories high. Occasional releases of UF_6 occurred during compressor disassembly. There were supervisory offices in the middle of the building.

C-315 Tails Withdrawal

The building was used for the removal of depleted UF_6 byproduct from cascade and stored in cylinders. The C-315 Tails Withdrawal Building was approximately 53 x 30 feet in size and contained four cart tracks and product equipment to accommodate four 10 to 14 ton cylinders. Four roll-up doors were located in the east wall to permit the entry and exit of the cylinders (Fig. 2). The west wall contained doors to the pump room and control room. Thus, there were six penetrations (doors) affecting air current flow in the building.

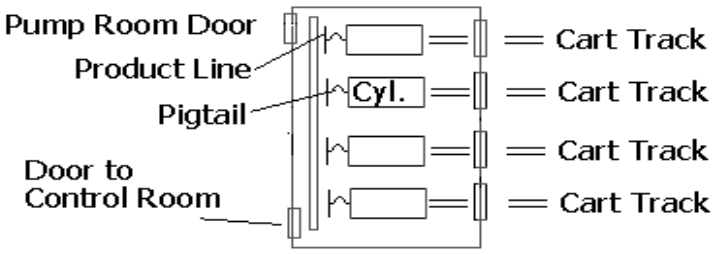

Figure C-4. Schematic diagram of Building C-315 Tails Withdrawal Area

The liquefaction was accomplished by compression of the UF_6 flowing to the building from the enrichment operation (Buildings C-331, C-333, C-335, C-337) at a pressure which the UF_6 gas can be conveniently liquefied. After condensing, the liquid was allowed to conveniently flow into the cylinders. The product was drained as a liquid into the multi-ton cylinders through a copper tube referred to as a pigtail (note the drawing above). When the cylinder was filled to its capacity, the cylinder and drain valves were closed and the pigtail was evacuated and purged. The pigtail was then disconnected at the cylinder valve.

The C-315 Building began operation in early 1953. At that time, the ventilating system provided approximately 800 cubic feet/minute (CFM) exhaust in three registers near the floor along the west wall and 400 CFM of supply discharged about 9 feet above the floor from four registers. Other make up air entered from the control room and through an opening in the east wall. The system was modified two months later by extending the local exhaust ducts to hood installed above the pigtail connections.

In 1980, the building was normally manned by 1-3 persons with a crane operator on call should cylinder transfer involving crane movements be required. The workers were responsible for completing equipment checks, logging equipment data, preparing cylinders for filling, disconnecting and weighing the full cylinders, transferring cylinders, and maintaining cylinder records.

By 1997, the workforce consisted of operators (2/3 shift), maintenance mechanics (4/shift), electricians (2/shift), janitor (1/shift) and foremen (4/shift).

C-310 Product Withdrawal Building

This was where enriched UF_6 product was removed from the cascade and put into cylinders for transport. The C-310 Product Withdrawal Building was approximately 53 x 30 feet in size and contained two roll-up doors, one employee access door and double doors to the storage room. The building was equipped to handle two 10 to 14 ton cylinders at a given time (Fig. C-5).

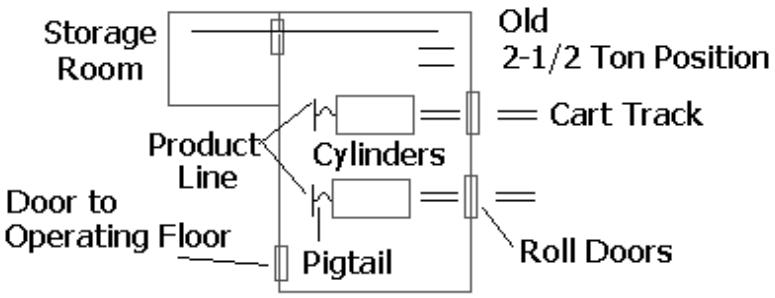

Figure C-5. Schematic diagram of Building C-310 Product Withdrawal Area

The C-310 Building began operation in early 1953. The ventilation as originally installed provided 900 cubic feet per minute (CFM) exhaust across four registers near the floor of the east wall. The ventilation was modified three months later to accommodate local exhaust hood positions over the pigtails. Two of the old 2-1/2 ton positions have small hoods with flexible ducts which are not in use but remain as part of the exhaust system. The present ventilation flows are approximately 20% greater than the flow rates experienced after the modifications were originally completed. While the initial ventilation modification (early 50's) resulted in less exhaust than the original design, the changed design and position of the hood close over the cylinder connection resulted in much more efficient control of the residual puff from the pigtail or valve seat leakage.

In 1980, the building was normally manned by 1-3 persons with a crane operator on call should cylinder transfer involving crane movements be required. The workers were responsible for completing equipment checks, logging equipment data, preparing cylinders for filling, disconnecting and weighing the full cylinders, transferring cylinders, and maintaining cylinder records.

In 1997, the workforce consisted of operators (3-7/shift), maintenance mechanics (4/shift),

instrument mechanics (2/shift), electricians (2/shift) and foremen (4/shift).

C-410 Feed Plant

The UF_6 for the cascades was generated in this building until the late 1970's. This building contained eight fluorination towers that were used for the conversion of UF_4 to UF_6. These towers were multistory structures where UF_4 was introduced at the top while fluorine gas was introduced at the bottom. The apparatus also contained at least one cyclone near the bottom. The system emptied into an ash receiver at the bottom. Due to the accumulation of uranium daughter products, transuranics and fission products, the ash receivers were at a high potential for increased radiation exposure.

The workforce consisted of operators (2/shift), maintenance mechanics (2/shift), instrument mechanics (1/shift), lab technician (1/shift).

C-420 Oxide Conversion Plant

This was where U_3O_8 was converted to uranium oxide and then to green salt for use as feed stock for the fluorination towers in C-410. Its operation was discontinued in 1980.

C-420 was a comparatively small building that was attached to the west side of C-410. It contained fluidizing beds that were used in the conversion processes. U_3O_8 (yellow) was first reduced to UO_2 (black) using a hydrogenation reaction. The resulting UO_2 was converted to UF_4 by reaction with fluoric acid (HF).

The equipment for doing these processes consisted of a series of hoppers, conveyer belts, screws, chutes, etc. which were susceptible to mechanical failure. When this happened, the system would be opened up and the operators and maintenance mechanics would do whatever was necessary to get things going again. Actually, the operations in C-420 do not appear to have had the potential for increased radiation exposure, but the workers in this building were rotated with those in C-410 to minimize individual radiation exposure.

The workforce consisted of operators (4/shift), maintenance mechanics (2/shift), electricians (2/shift), instrument mechanics (2/shift), and janitors (1/shift).

C-340 Uranium Metals Building

Several operations were performed in this building, two of which presented a high potential for increased worker radiation exposure. These were the conversion of depleted UF_6 to UF_4 using a hydrogenation process and the conversion of some of the UF_4 to uranium metal via a reaction with magnesium.

The rationale for doing the hydrogenation was to recover hydrofluoric acid for use in the oxide conversion process in C-420. Another reason may have been to convert UF_6 into a form that was easier to store. Both of the about processes generated considerable amounts of dust.

The building also contained a re-melt furnace for recasting uranium. After the above operations were shut down in the late 1970's, the building was used for offices and training programs.

The workforce consisted of operators (10-20/shift), maintenance mechanics (3-5/shift), instrument mechanics (3-5/shift), and electricians (3-5/shift).

C-409 Stabilization Building and three storage trailers

During the cascade improvement program of 1973 to 1981, there was a converter shop in this building for rebuilding converters. The building also had a small spray booth for minor cleaning jobs. The number of personnel involved is not known.

C-710 Technical Services Building

Underground storage tanks.

A. Gas cylinder storage building.
B. Storage facility.
C. Analytical chemistry and technical operations.

C-746B South Warehouse

Metal, furnace scrap recovery. This was the site of the smelter operations.

C-749 Uranium Scrap Burial Yard

Pyrophoric uranium metal shavings were disposed of in the C-749 burial ground from 1957-1977.

C-360 Shipping

This building was used primarily for shipping product from the plant. It did contain a two story high facility for transfer of UF_6 between different sized cylinders.

APPENDIX D

Doses, Exposures or Transuranic Material Concentrations Relative to Specific Worker Job Descriptions and Plant Locations

Introduction:

The following table includes radiological data for specific worker job descriptions and plant locations. This information was found in PGDP reports, records, and assessments. It might help to determine doses in these areas. Information in the table includes: plant action levels, dose rate information, personnel dosimetry information, summary report data, air, dust, or spill amounts or concentrations, etc. The reader is cautioned to go to the original reference to get the proper understanding of the available information. Plant locations are indicated by numbers (e.g., 1,2,3), the references are identified by letters (e.g., a, b, c) and are listed at the end of the Table.

Job/ Work Area Descriptions	Plant Location	Radiological Data found in PGDP Reports, Records, and Assessments
Ash handling (hot hauling)	**1.** C-400 **2.** C-410 **3.** C-746B	1-a Film badge reading >600 mrem beta; Jan. 1956 film badge max. 1055 mr/wk, avg. 72 mr/wk; Feb. 1956 film badge max. 395 mr/wk, avg. 48 mr/wk, 2 penetrating radiation personnel exposures over the PAL, 315 and 325 mr/wk; Mar. 1956 film badge max. 470 mr/wk, avg. 42 mr/wk; Apr 1956 film badge max. 330 mr/wk, avg. 42 mr/wk. 1-a Max beta gamma 915 mr/wk, max. gamma 265 mr/wk 1-e 3.3E-13 µCi/cc air TRU 1-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3. 1,2-a U bioassay 25µg/day, Pu bioassay 1/10 MPL, 9 persons on uranium restriction. 1,2,3-d Am-241 7.2E3 dpm/ml; Pu 5.7E4 dpm/ml; Np 4.52E4 dpm/ml; Depleted U 3.6 E4 dpm/ml; Tc 1.65E5 dpm/ml. 2-a Np 2.5 dpm/8hr collection; external <10 rad; skin dose 6.5 rad; U bioassay max. > 8 mg/l, avg. 0.238 mg/l 2-b U bioassay max. > 8 mg/l, avg. 0.238 mg/l. 2-a 6 film badges exceeded allowable limits, max beta gamma 1735 mr/wk, max gamma 315mr/wk; air concentration max 158 beta dpm/ft^3, avg. 48 beta dpm/ft^3; 9 film badges above the PAL; 41 of the 94 uranium air concentration samples exceeded the MAC, avg 1.57 cpm/ft^3 2-b Gamma 1000 mrem/hr, beta 75–100 rad/hr. 3-c Furnace liner U 3800 ppm, Tc <0.001ppm, Np 862 ppb, Pu 0.12 ppb, Th 0.48 ppb. Slag U 308 ppm, Tc 0.48ppm, Np 54 ppb, Pu 0.06 ppb. HF-Trap U 4 ppm, Tc 0.003ppm, Np 1 ppb, Pu 0.005 ppb, Th 0.03 ppb
Building Access	**1.** C-340	1-a 7 out of 13 Uranium urine concentrations greater than 10 microgram /liter, avg. is 12 1-d Am-241 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml
Cascades, Product Withdrawal and Tails Withdrawal	1. C-315 2. C-331 3. C-333 4. C-335 5. C-337 6. C-310	1 to 6-a,g Np dust, 0.002 to 0.370 mg/g dust 5-g Np 18,000-506,000 dpm/g, Pu 352-648 dpm/g dust 6-a U bioassay avg. 0.457 mg/l 1-a 100-170 mr/wk film badge. Avg. 12-29 1-a Max beta gamma 60, max gamma 40 mr/wk *-h 1,340,000dpm gram Np in the dust
Cold Trap and Refrigeration		1-i 20 dpm/m^3 alpha for 240 hours per year, or 4 AMAD, 2 operators inhaled 1-2 mg soluble U 1-h Up to 50 rad/hr beta at cooler line

Crane Operation	1. C-400 2. C-410 3. C-420 4. C-331 5. C-333 6. C-335 7. C-337 8. C-340	1-a Film badge reading >600 mrem beta 1-a Max beta 915 mr/wk, max gamma 265 mr/wk 1-e 3.3E-13 Ci/cc air TRU 1-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3. 1,2-a U bioassay 25 µg/day, Pu bioassay 1/10 MPL 1,2,3,6,8-d Am-241 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml 2-a Np 2.5 dpm/8hr collection; external <10 rad, skin dose 6.5 rad; max beta gamma 1735 mr/wk, max gamma 315mr/wk; air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3, 41of the 94 uranium air concentration samples exceeded the MAC, the average is 1.57 cpm/ft^3. U bioassay max > 8 mg/l avg 0.238 mg /l. 2-i 10 dpm/m^3 alpha for 320 hours per year 3-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year 4-a U bioassay avg 0.085 mg/l 7-h breathing zone Np 237 dpm/m^3
Cylinder Heel Cleaning	1. C-400	1-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 1-a Jan 1956 film badge max 1055 mr/wk, avg 72 mr/wk. Feb 1956 film badge max 395 mr/wk, avg 48 mr/wk. 1-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 1-f,1-g Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U15-150 alpha dpm/m^3, Np 237 8-75 alpha dpm/m^3, Pu 239 8-75 alpha dpm/m^3
Deblading of compressor rotor & stator	1. C-400	1-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 1-a max beta gamma 915 mr/week, max gamma 265 mr/wk 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 1-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3

Disassembly of stuck G17 cell block valves	C-720	1-a Elevated alpha's 1-f 671,000 dpm/g alpha's around stator blade 1.1% Np, breathing zone 24,000 dpm/m^3, 1 % Np, while removing stub shafts 1-j Uranium concentration in urine range from 0 to 13000 µg/l 1-k 880,000 dpm/g with 53% trace, breathing zone analysis 150dpm/m^3 from trace and 96 dpm/m^3 from uranium

Drum Crushing	C-746	1-l Furnace liner U 3800 ppm, Tc <0.001ppm, Np 862 ppb, Pu 0.12 ppb, Th 0.48 ppb. Slag U 308 ppm, Tc 0.48ppm, Np 54 ppb, Pu 0.06 ppb. HF-Trap U 4 ppm, Tc 0.003ppm, Np 1 ppb, Pu 0.005 ppb, Th 0.03 ppb
Drumming green salt green salt plant operations	1. C-340 2. C-420	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U - 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml 2-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year
Electrical	1. C-410	1-a Jan 1956 film badge max 140 mr/wk, avg 15 mr/wk. Feb 1956 film badge max 580 mr/wk, avg 27 mr/wk 1-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3
Fabrication	C-720	1-j Uranium concentration in urine ranged from 0 to 13000 µg/l 1-k 880,000 dpm/g with 53% trace breathing zone analysis, 150dpm/m^3 from trace and 96 dpm/m^3 from uranium
Fires	1. C-310 2. C-337	1-a U bioassay avg 0.457 mg/l
Firing reduction vessels (bombs) to make derbies	1. C-340	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml
Flange grinding	1. C-340 2. C-400 3. C-410 4. C-420	1,2,3,4-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml 2-e 3.3E-13 µCi/cc air TRU 2-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk 2-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3 2,3-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 3-a Np 2.5 dpm/8hr collection 3-a External <10 rad, skin dose 6.5 rad 3-i 10 dpm/m^3 alpha for 320 hours per year 3-a U bioassay max > 8 mg/l, avg 0.238 mg/l 3-f 6 film badges exceeded allowable limits, max beta gamma 1735 mr/wk, max gamma 315mr/wk, air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 4-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year

HF collection and transfer to C-410	1. C-340	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml

Machining	1. C-720	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-j uranium concentration in urine range from 0 to 13000 µg/l 1-k 880,000 dpm/g with 53% trace, breathing zone analysis 150 dpm/m^3 from trace and 96 dpm/m3 from uranium
Maintenance on roof Maintenance (feed plant) (instrument) (utility)	1. C-340 2. C-410	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U - 3.6 E4 dpm/ml, Tc 1.65E5 dpm/ml 2-a Jan 1956 film badge max 580 mr/wk, avg 82 mr/wk. Feb 1956 film badge max 520 mr/wk, avg 61 mr/wk 2-a Max beta gamma 1735 mr/wk, max gamma 315mr/wk. Air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 2-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3
Midnight Negatives	1. C-331 2. C-333 3. C-335 4. C-337	1-a U bioassay avg 0.085 mg/l 2-e 1.2E-13 µCi/cc air U 3-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml
Mixing UF4 powder with Mg powder loading into the bomb	1. C-340	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml
Neptunium Recovery	1. C-400 2. C-710	1-a Jan 1956 film badge max 1055 mr/wk, avg 72 mr/wk. Feb 1956 film badge max 395 mr/wk, avg 48 mr/wk 1-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 2-a Np is 29% of air samples
Product withdrawal during normal operations	1. C-310	1-a U bioassay avg 0.457 mg/l 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-g Np < 0.005 mg/g of dust
Pulverize operations and maintenance	1. C-400	1-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk, 2 film badges above the PAL 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 1-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np-237 8-75 alpha dpm/m^3, Pu-239 8-75 alpha dpm/m^3

Release Response	1. C-331 2. C-333 3. C-335 4. C-337 5. C-310 6. C-315 7. C-340 8. C-400 9. C-410 10. C-420	1-a U bioassay avg 0.085 mg/l 2-e 1.2E-13 µCi/cc air U 3,5,7,8,9,10-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 5-a U bioassay avg 0.557 mg/l 5-g Np < 0.005 mg/g of dust 6-a Max beta gamma 60 mr/wk, max gamma 40 mr/wk 6-a Jan 1956 film badge max 120 mr/wk, avg 21 mr/wk. Feb 1956 film badge max 100 mr/wk, avg 12 mr/wk 8-e 3.3E-13 µCi/cc air TRU 8-f Breathing zone U daughters 32-320 beta dpm/m^3, Tc-99 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3 9-a to 9-h U bioassay max > 8 mg/l, avg 0.238 mg/l 8,9-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 9-a Skin dose 6.5 rad, Np 2.5 dpm/8hr collection 9-i 10 dpm/m^3 alpha for 320 hours per year 9-a Max beta gamma 1735 mr/wk, max gamma 315mr/wk 8-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk 9-a 41 of the 94 uranium air concentration samples exceeded the MAC, the average is 1.57 cpm/ft^3 10-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year
Removal of 000 compressor stub shaft	1. C-720	1-j Uranium concentration in urine range from 0 to 13000 µg/l 1-k 880,000 dpm/g with 53% trace, breathing zone analysis, 150dpm/m^3 from trace and 96 dpm/m^3 from uranium
Removal of Converter shell internal fixtures	1. C-409	1-n Alpha activity, 11% Np, 3% from Pu, 86% U, Beta activity, 49% Tc, 51% Uranium daughters 1-f Breathing zone, U daughters 32-320 beta dpm/m^3, Tc 288-2878 beta dpm/m^3, U 15-150 alpha dpm/m^3, Np 8-75 alpha dpm/m^3, Pu 8-75 alpha dpm/m^3
Replacement of UF_6 Cylinder valve	Outside C-400	1-a 5E5 α/min (surface reading) 1-a 450 mrad β exposure 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-o On the spot UA showed 2.3 mg/l U, two hours later 13 mg/l U, 48 hours later 75 µg/l
Slag recovery	C-340 slag plant	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-c Slag U 308 ppm, Tc 0.48ppm, Np 54 ppb, Pu 0.06 ppb
Smelting	1. C-746	1-c Furnace liner U 3800 ppm, Tc <0.001ppm, Np 862 ppb, Pu 0.12 ppb, Th 0.48 ppb. Slag U 308 ppm, Tc 0.48ppm, Np 54 ppb, Pu 0.06 ppb. HF-Trap U 4 ppm, Tc 0.003ppm, Np 1 ppb, Pu 0.005 ppb, Th 0.03 ppb 1-p Al has Np 26 ppb, Pu 0.03 ppb, Tc 50 ppb, U 54 ppm. Ni has Np 43 ppb, Pu 0.05 ppb, Tc 0.9 ppb, U 138 ppm. Steel has Np 0.53 ppb, Pu <0.005 ppb, Tc <10 ppb, U 8.9 ppm, U 0.048 ppm

Technetium recovery	1. C-400	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 1-a Jan 1956 film badge max 1055 mr/wk, avg 72 mr/wk. Feb 1956 film badge max 395 mr/wk, avg 48 mr/wk. Mar 1956 film badge max 470 mr/wk, avg 42 mr/wk. Apr 1956 film badge max 330 mr/wk, avg 42 mr/wk 1-a Max beta gamma 915 mr/wk, max gamma 265 mr/wk
UF_6 reduction to UF_4	1. C-340	1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml
Unplugging feed plant transfer lines	1. C-410 2. C-420	1-i 10 dpm/m^3 alpha for 320 hours per year 1-a U bioassay max > 8 mg/l, avg 0.238 mg/l 1-a Jan 1956 film badge max 580 mr/wk, avg 61 mr/wk. Feb 1956 film badge max 595 mr/wk, avg 48 mr/wk. Mar 1956 film badge max 425 mr/wk, avg 46 mr/wk. Apr 1956 film badge max 370 mr/wk, avg 45 mr/wk 1-a Max beta gamma 1735 mr/wk, max gamma 315mr/wk, air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 1,2-a U bioassay 25µg/day, Pu bioassay 1/10 MPL, 1,2-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 2-a Np 2.5 dpm/8hr collection 2-a External <10 rad, skin dose 6.5 rad 2-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year 2-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3
Fluorination tower operations and unplugging fluorination towers	1. C-410	1-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 1-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-i 150 dpm/m^3 UO_2F_2 for 100 hours per year, 80 dpm/m^3 alpha for 120 hours per year 1-i 10 dpm/m^3 alpha for 320 hours per year 1-a U bioassay max > 8 mg/l, avg 0.238 mg/l 1-a 9 film badges above the PAL, max beta gamma 1735 mr/wk, max gamma 315 mr/wk, air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 1-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3
Uranium powder conveyors, hopper etc.	1. C-410 2. C-420	1,2-a U bioassay 25 µg/day, Pu bioassay 1/10 MPL 2-a Np 2.5 dpm/8r collection, external <10 rad, skin dose 6.5 rad 1,2-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1,2-i 80 dpm/m^3 U for 220 hours per year, 10 AMAD 2-a 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year 1-i 10 dpm/m^3 alpha for 320 hours per year 1-a U bioassay max > 8 mg/l, avg 0.238 mg/l, max beta gamma 1735 mr/wk, max gamma 315 mr/wk, air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 1-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3

Uranium Recovery (solvent extraction)	1. C-400	1-d Am-241 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 1-e 3.3E-13 µCi/cc air TRU 1-a Jan 1956 film badge max 1055 mr/wk, avg 72 mr/wk. Feb 1956 film badge max 395 mr/wk, avg 48 mr/wk. Mar 1956 film badge max 470 mr/wk, avg 42 mr/wk. Apr 1956 film badge max 330 mr/wk avg 42 mr/wk
Welding	1. C-410 2. C-420 3. C-720	1-i 10 dpm/m^3 alpha for 320 hours per year 1-a U bioassay max > 8 mg/l, avg 0.238 mg/l 1-a Max beta gamma 1735 mr/wk, max gamma 315 mr/wk, air concentration max 158 beta dpm/ft^3, avg 48 beta dpm/ft^3 1-a 41 of the 94 uranium air concentration samples exceeded the MAC the average is 1.57 cpm/ft^3 1,2-a U bioassay 25µg/day, Pu bioassay 1/10 MPL 2-a Np 2.5 dpm/8hr collection, external <10 rad, skin dose 6.5 rad 3-a to 3-a elevated alpha's 1,2,3-d Am 7.2E3 dpm/ml, Pu 5.7E4 dpm/ml, Np 4.52E4 dpm/ml, Dep U 3.6E4 dpm/ml, Tc 1.65E5 dpm/ml 2-i 100 dpm/m^3 alpha for 180 hours per year, 10 dpm/m^3 alpha for 150 hours per year 3-j Uranium concentration in urine range from 0 to 13000 µg/l 3-k 880,000 dpm/g with 53% trace, breathing zone analysis 150 dpm/m^3 from trace and 96 dpm/m^3 from uranium
Toll transfer and sampling building	1. C-360	1.e 1980 dpm/100 cm^2 TRU removable surface contamination, 2940 dpm/100 cm^2 U removable surface contamination

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h. *Total Body Counter for Paducah*
Identifier (source/publisher): Union Carbide
Author: R.A. Winkel
Date: February 16, 1962

i. Exposure Assessment - Uranium Recycle Materials in the Paducah Feed Plant
Identifier (sponsor/publisher): Martin Marietta Energy Systems, Inc.
Author: R. C. Baker
Date: July 23, 1987

j. Memorandum (Call from W. Johnson)
Identifier (sponsor/publisher): Oak Ridge Associated Universities
Author: CC Lushbaugh
Date: March 11, 1986

k. Health Physics Inspection Report Identifier
Identifier (sponsor/publisher): Paducah Health Physics Department
Author: BE McDougal
Date: March 1962

l. Effect of Ammonia-Steam Pretreatment of Nickel Oxide and Radionuclide Contaminants in Nickel Smelted at C-746
Identifier (sponsor/publisher): PGDP
Author: R. E. Simmons
Date: May 24, 1982

m. Former Worker Medical Surveillance Program at Department of Energy Gaseous Diffusion Plants
Identifier (sponsor/publisher): Unknown
Authors: Unknown
Date: October 1, 1997

n. *Health Physics Inspection Repor*t
Identifier (sponsor/publisher): Paducah Health Physics Department
Author: KA Davis
Date: November 4, 1976

o. Memorandum (Call from W. Johnson)
Identifier (sponsor/publisher): Oak Ridge Associated Universities
Author: CC Lushbaugh
Date: February 5, 1986

p. Paducah Scrap Metal Contamination Level Before and After Smelting
Identifier (sponsor/publisher): Union Carbide
Author: S. M. Leone
Date: March 29, 1983

APPENDIX E

Year, Radiological Limits, Building and Jobs, Monitoring Methods and Frequency, Regulatory Manuals Cited, and Documented Exposures

Year	Ref* Comp.	*LIMITS*	Building (Job)	Monitoring	Manuals Cited	Documented Exposure
1952	52-07-01	3 rad γ skin 6 rad γ whole body		Film badges and urinalysis		Np average over 4 men 2.5 dpm in urine 1 person received exposure of 5.5 rad to skin
Jan – March 1958	52-07-01	3.75 rad γ/quarter 7.5 rad γ and β/quarter		-Film badge monthly for 200 people quarterly for the remainder -Pu exposure assessed by ORNL indicates body content below $^{1}/_{10}$ MPBB	Standard Practice Procedure Manual (plant document)	
April – June 1958	52-07-01	3.75 rad γ /quarter 7.5 rad γ and β /quarter 50 μg of Uranium/day		Urinalysis	NBS Handbook 52	Ave U content 10μg/L of urine 66% were below average
July-Sept 1958	52-07-01	3.75 rad γ /quarter 7.5 rad γ and β /quarter		Urinalysis		Max exposure 6.5 to skin ave 11μg/L of urine
Oct – Dec 1958	52-07-01	3 rad γ 7 rad γ and β		Urinalysis Continuous air monitoring for α activity during Np recovery		Np $^{1}/_{10}$ MPC for Uranium or equal to MPC for Np (< 15% due to Np) 66% of urinalysis shows less than 10 μg/L urine
Jan – March 1959	52-07-01	3 rad γ /13 week 6 rad γ and β / 13 week				Ave. 11μg/L of urine 26 people excreted as much as 12 but less than 25 μg/L
April – June 1959	52-07-01	3 rad γ /13 week 6 rad γ and β / 13 week	feed plant operations	Film badge reading changed from 1 week readings to 1 month Urinalysis Air sampling		Ave U 9 μg/L of urine 75% were below 10 μg/L of urine 35 people excreted as much as 12 μg/L of urine

Year	Ref* Comp.	*LIMITS*	Building (Job)	Monitoring	Manuals Cited	Documented Exposure
July-Sept 1959	52-07-01	3 rad γ /quarter 6 rad γ and β / quarter		Urinalysis		Ave U 7 µg/L of urine 80% were below 10 µg/L of urine 18 people excreted as much as 12 µg/day after exposure ended ORNL reports 0.21 dpm for urinalysis checked for gross α excluding U
Oct – Dec 1959	52-07-01	3 rad γ /13 week 6 rad γ and β / 13 week		Urinalysis 71 dust samples collected for Np analysis Badges changed from weekly to monthly cycle		72% were below 10 µg/L of urine 13 people excreted as much as 12 but less than 25 µg/day
1960	Union Carbide 61-09-01	Surface: Uranium 2000 dpm/cm^2 β.γ 0.3 mrad/hr Air: Uranium 110 dpm/m^3 Pu-239 & Np-237 10 dpm/m^3 Film Badges: γ 3 rad β-γ 6 rad	C-310, C-315, C-400 (chemical cleaning, janitor, laundry and test loop, maintenance), C-410 (instrument maintenance, feed plant maintenance, operations, janitors), C-340 (maintenance, operations) C-331, 333, 335, 337 (process maintenance), C-410 (electrical maintenance) C-410 (laboratory), C-710 (laboratory sampling), C-720 (Maintenance, shift personnel, Utility crew, piping and insulation,	Urinalysis – Monthly Urinalysis- every 2 months Urinalysis – ever 3 months Urinalysis – every 4 months Urinalysis – every 6 months Urinalysis – every 12 months or greater Film badge for all employees	Standard Practice Procedure Manual (plant document) NCRP in NBS handbook 69 AEC Manual, Chapter 0524, paragraph 02 e NBS Handbook 52	Yes, gives plant film badge exposure ranges for 1955-1960

Year	Ref* Comp.	*LIMITS*	Building (Job)	Monitoring	Manuals Cited	Documented Exposure
			lubrication, Welding, Pipe fabrication, Sheet metal shop, compressor shop, converter shop) C-310, 315, 331, 333, 335, 337 & 340 (instrument maintenance) C-331, 333, 335, 337, C-720 (roads, grounds masonry, & Cylinder crew, carpentry services, paint shop) Other			
1962	Union Carbide 62-09-02		C-340, 400, 410 (operations) All others C-310, 315, 340, 400, 410	Film badge checked every 4 weeks Film badge – checked every 12 weeks Urinalysis – every 4 weeks		
1974-1978	80-07-01	In vivo exposure-max. limit of 5 rem Lung exposure-max. limit of 15 rem/year				

APPENDIX F

Worker Exposure Scenarios

Introduction to Worker Occupational Exposure Scenarios

This is a general overview of the types of occupations or operations and their usual locations (by building). Of interest are the types of duties that these workers were doing and possible radiological hazards that may have been involved. Much of the information obtained in these "scenarios" was obtained from the worker interview transcripts. The references to specific transcripts are indicated as, for example, "C01CD116". These transcripts have been de-identified (without worker names or social security numbers).

These scenarios were used with the other data and information to create general risk categories for the worker groups and occupations. This "risk mapping" is found in Table 6.1, in the report. The following exposure scenarios (a subset of Table 6.2) are discussed in detail in this appendix.

INDEX

Operations	Workers	Location
Ash receivers and fluorination Towers	Operators and maintenance mechanics	C-410 Feed plant
Cylinder heels	Operators, cylinder movers	C-410 Feed plant
Cylinder heels cleaning	Operators	C-410 Feed plant
Derby processing	Operators	C-340 Metals
Pulverizer operations	Operators and maintenance mechanics	C-400
Unplugging and maintaining oxide Conversion equipment	Operators and maintenance mechanics	C-420 Oxide Conversion Plant
Cascade maintenance	Operators and maintenance mechanics	C-331, C-333, C-335, C-337
Baghouse cleaning	Operators	C-400, C-410, C-420, C-340
Hydrogenation tower cleaning and maintenance	Operators and maintenance mechanics	C-340 Metals
Spray cleaning operations	Operators	C-400
Flange grinding	Maintenance mechanics and machinists	C-720 Cascades
Green salt sweeping and Drumming	Operators and janitors	C-400, C-410, C-420, C-340
Disassembly of compressors and Block valves mechanics	Maintenance mechanics, compressor	C-720
Fluorine cooling tower Carpentry	Carpenter	C-340
Baghouse cleaning (cascades)	Operators	C-331, C-333, C-335, C-337
Instrument maintenance	Instrument mechanics	Cascades C-400, C-410, C-420, C-340, C-310, C-315
Machine Shop	Machinists	C-720
Electric work		Electricians All
Product withdrawal	Operators	C-310, Product withdrawal
Tails withdrawal	Operators	C-315, Tails withdrawal
Crawling the pipes	Operators, welders	C-331, C-333, C-335, C-337

Operations	Workers	Location
		Cascades
Midnight negatives	Everyone outside the cascades	Vicinity of Cascades
Fire suppression	Firefighters	C-310, C-315, C-720

Operation: Ash receivers and fluorination towers
Workmen: Operators and maintenance mechanics
Building: C-410, Feed Plant

Summary of operation:

UF_4 was converted to UF_6 in the fluorination tower. The ash or residue was collected at the bottom into a container called the ash receiver.

Potential for increased radiation exposure:

Potentially higher from inhalation of dust during changeovers of the ash receivers and various maintenance operations, especially if the personal protection equipment was not used. Also, higher levels of beta and gamma emitters accumulate at the ash receiver resulting in a need to restrict the amount of time the workers could work in this area. Others in the building could also be exposed to the ambient dust.

Detailed Description:

The ash handling operation was performed in C-410. The ash receiver was located at the bottom of the ash tower in a small four-foot by four-foot shed (CD116). The ash receiver was clamped on the ash tower via a flange, with C-clamps. The ash tower was a ~10" diameter pipe which ran from the basement and was about three stories high (~30 feet)(D02CD105). There were eight towers. Each one would be placed online for 24 to 36 hours, after which it would be changed out.

UF_4 and fluorine gas were fed in at the top of the tower. The UF_4 was then converted into UF_6 and was withdrawn as the product of Building C-410.

At one or two day intervals, the ash receiver would be changed on one of the towers (D02CD105). At the changing out of the ash receivers, the operators were given Army assault masks. They sometimes wore rain suits or might wrap wet towels around their necks to prevent HF burns.

C-410 was an open building and the ash receiver area was not isolated from the other operations, which took place in the building. Vacuum hoses were used to remove the ashes and dust during the ash receiver changeovers. Apparently, there were occasions when the vacuum hoses were not adequate. D02CD105 reported that there were occasions when the mist resulting from the change over obscured the men performing the operation. In some instances, a haze formed in the top of

the building. There were times when the resulting dust covered everything in the building including the lunchroom tables that were located in the control tower.
As stated above, C-410 was an open building. The other employees were given half-mask respirators and instructed to use them when they could see a mist.

D02CD105 shared hearsay information that was passed around the men that the urinalysis collections of the ash handlers were always taken just before doing a changeover so that they would show minimum radioactivity. This seemed to be recollection shared by some other workers.

D02CD105 also reported that there were occasions when an online ash tower would develop a leak before it was due to be taken offline. When this occurred the vapor was permitted to vent into the building until the cycle was completed.

Another job with a high potential for increased worker radiation exposure was that of unplugging towers that became blocked due to operator inattentiveness (D01CD116). This was reportedly done by removing the ash receiver and replacing it with a barrel. The worker would stand under the tower and beat the plug with a six-foot steel rod. Optimally, the ash would fall into the barrel otherwise; it would be shoveled and swept up off the floor. On some occasions, the worker would be covered with black soot. It was also claimed that there were no extra decontamination procedures after. The worker performing this operation would wear a respirator, but some reported occasional leaks through the respirator for unknown reasons.

Additional References
C01CD116 - Operator, C400, C410
C02CD105 - General worker, C410.

Operation: Cylinder heel exposure
Workmen: Operators, cylinder movers
Buildings: C-410

Summary of operation:

The heels are the residues that would accumulate in the UF_6 cylinders used to transport UF_6 from the fluorine towers to the input points of the cascades.

Potential for increased radiation exposure:

The potential external radiation exposure due to uranium daughter products and technetium often reached increased levels such that regulatory limits could be exceeded, depending on time and proximity of the work with the source.

Detailed Description:

Continual reuse of cylinders resulted in an accumulation of various insoluble uranium fluoride compounds that are referred to as "heels". Increased levels of gamma and beta radiation occurred when the tanks were empty because of the loss of the self-shielding effects of the uranium. For safety purposes, the amount of time workers spent in the vicinity of a tank was restricted to keep radiation exposures from exceeding regulatory limits.

Operation: Cylinder heels cleaning
Workmen: Operators
Buildings: C-400

Summary of operation:

As noted above, the cylinder heel material was very radioactive. There was a program to occasionally clean the tanks, exposing the workers to this radiological hazard.

Potential for increased radiation exposure:

The potential for radiological exposure was high. Aerosols were minimized during the process. The sludge resulting from the process was higher in radioactivity and working with this material was time restricted to keep radiation exposures below regulatory limits.

Detailed Description:

The cylinders were flushed out with a liquid solution. The resulting solution was then treated until it separated into a liquid component and sludge. The liquid component was then analyzed for radioactivity. If the values were acceptable, it was discharged into the drainage system. Otherwise, it was reprocessed. The sludge was loaded into barrels for storage. The transuranics, plutonium and neptunium and also the fission product, technetium, were also present in these materials.

Operation: Derby processing
Workmen: Operators
Building: C-340, metals

Summary of operation:

Derby processing is a method of converting UF_4 to uranium metal. In the process, large amounts of UF_4 uranium and other dust compounds are released into the air. This operation was hazardous because of the potential to ingest or inhale uranium metal.

Potential for increased radiation exposure:

Could be high, depending on the use and function of the respirators.

Detailed Description:

Derbies were made in a metal mold that was lined with insulating materials and refractory material. A mixture of UF_4 and magnesium was put in the mold, which was sealed and then fired in an induction furnace. The primary problems were spills, which occurred during derby setup when the insulating material and the UF_4 were being loaded. Additional dust was generated when the mold was broken open and the derby is removed. Finally, it was often necessary to manually remove defects from the derbies by chiseling and grinding.

Operation: Pulverizer operations
Workmen: Operators and maintenance mechanics
Building: C-400

Summary of operation:

Operators and workers in the surrounding environs were possibly exposed to large quantities radioactive materials in the form of aerosols. The main problem was the generation of excessive dust, both during routine operations and accidental situations.

Potential for increased radiation exposure:

The potential for exposures may have been high for both external, uranium and TRU exposures.

Detailed Description:

The pulverizer was a five-story stack type structure located in the far northeast corner of C-400. There was an opening at the top into which 55 gallon drums were emptied. The material was in the form of lumps and crushing was not involved. The drums themselves were picked up with a forklift and put on a conveyer belt (bucket elevator) where the lids were taken off. They were then run to the top of the pulverizer where they were dumped into a hopper. From there the material went into a feeder and a series of shakers where the material was pulverized. The pulverizer contained a jaw crusher, which would reduce the size of the particles. The operation also involved a screening process to obtain the correct sized particles. The product was dumped into large gray hoppers with dimensions of about 5' x 5' square x 6' tall which had a capacity of 7 tons. They usually processed about 12 drums a shift. Apparently, the pulverizer was partially contained in some type of housing because some workers reported being required to wear a respirator whenever they went inside the pulverizer.

An area with a width of approximately 150' was kept clear around the pulverizer. In addition, there was a dust collector for the pulverizer, which was separate from the building ventilation system. When spills occurred, the area was swept up at the end of the shift, otherwise it was

swept once a week or more often if necessary. Floor sweep was used for this operation. UO_3 and UF_4 were heavy powders, which did not remain airborne for long.

The most common spills occurred when barrels would be accidentally dumped. In such cases, UF_4, the workers report that the material would flow near to the lunchroom area. Another common problem was the operator losing track of the number of barrels in the pulverizer and accidentally overloading it. When this occurred, there would literally be an explosion of dust. The filter room contained several filter cans, which were about 8" in diameter and 18" tall. When required, the operators would don respirators and empty the filters into drums. This operation usually took about an hour. This may have been the same as the bag house cleaning in which case it was done about every six months.

Some of the older operators maintained that the pulverizer was one of the hottest places in the plant.

Air sampling was done in the area about the pulverizer. The samplers were positioned to capture the dust in the vicinity of the pulverizer.

Ash receivers were stored in C-746 until they had cooled down enough to move to the C-400 pulverizer. Operators wore respirators when they were drumming.

The pulverizer would, on occasion, become plugged and this required that the workers manually unplug it with metal rods. There were also some shear pins in the rotary devices, that when broken, would require a worker to get inside to replace them.

When spills occurred, the main people affected were two or three operators as well as any cylinders cleaners who were using the hallway to work in. Otherwise, no one was immediately involved.

They once had a uranium fire in or near the pulverizer.

References:

D01CD061
D01CD002
D01CD116
D03CD137
D03CD133
D07CD007
D07CD036
D24CD045
D24CD129
D25CD128
D14CD102
D14CD010

D15CD058
D16CD122
D16CD42
D19CD130
D12CD035
D13CD090
D13CD052

Operation: **Unplugging and maintaining oxide conversion equipment**
Workman: **Operators and maintenance mechanics**
Building: **C-420, Oxide Conversion Plant**

Summary of operation:

The equipment for converting UO_3 to UF_4 included fluidizing beds, conveyers, stacks and hoppers that were subject to breakdown, jamming and spills. When this happened the workers were subjected to excessive dust exposures.

Potential for increased radiation exposure:

High for inhalation, especially if respirators were not used. The potential was less than in C-410 because radioactive materials did not accumulate in the oxide conversion process.

Detailed Description:

UO_3 was converted to UF_4 using fluidizing bed technology. There were several points where the system was subject to breakdown or jamming. When this happened, the workmen were exposed to excessive dust.

Operation: **Maintaining cascade equipment (normal operations)**
Workmen: **Operators and maintenance mechanics**
Building: **C-331, C-333, C-335, C-337**

Summary of operation:

UF_6 releases when the cascades were opened for normal upkeep and repairs.

Potential for increased radiation exposure:

Could be high under some circumstances.

Detailed Description:

Under normal operating conditions, the processing plant presented a lower potential for worker radiation exposure than did C-400, C-410, C-420 and C-340. The major reason for this was that most of the piping in the cascades was under negative pressure which meant that leaks resulted in atmospheric air being drawn into the piping rather than loss of UF_6 into the ambient environment.

On occasion, the process lines were opened up to service or replace compressors or block valves. When this happened a negative reading for UF_6 gas was supposed to be obtained before the lines were opened. For various reasons, production schedules, technical problems, etc., this was not always done and there would be a release of UF_6 gas when the system was opened. Even when the system was clear, residual UF_6 gas in the micropores of the piping would react with moisture in the air to form a uranyl fluoride coating on the pipe surface (see pipe crawling below). Excessive inhalation of the materials could occur because of the release and residual compounds, which were present when the work was done.

This situation was aggravated by the common practice of having workers crawl inside the pipes to remove debris and do mechanical work.

Operation: **Baghouse cleaning for C-400, C-410, C-420 and C-340**
Workmen: **Operators**
Buildings: **C-400, C-410, C420, C-340**

Summary of operation:

The baghouses contained the filters for the air cleaning system for the buildings. The primary function was to remove radioactive materials. At periodic intervals they needed to be cleaned. This was a very dusty job where the use of respirators was mandated.

Potential for increased radiation exposure:

High for inhalation.

Detailed Description:

Baghouses are rooms where the filters are located for removing radioactive materials from the air in buildings where it is present. It is a small room where the filters are periodically removed and the apparatus is cleaned. Copious quantities of dust are generated. Baghouse cleaning is the one job where respirators were mandated and not left to the discretion of the workman. The reason why the above buildings presented a greater potential for increased radiation exposure to the workers than the cascades was the presence of transuranics and fission products in the air of those buildings.

Operation: **Cleaning and maintaining the hydrogenation towers**
Workers: **Operators and maintenance mechanics**
Building: **C-340, Metals Building**

Summary of operation:

The conversion of depleted UF_6 gas to UF_4 was done with towers where the UF_6 was mixed with hydrogen gas. As with the other towers at PGDP, the hydrogenation towers would plug up and/or require general maintenance. When this happened, the system would be opened up and dust clouds could be generated.

Potential for increased radiation exposure:

Probably moderate.

Detailed Description:

This was another one of the many dusty operations at PGDP. The dust was relatively benign compared to that from say the feed plant, because it likely did not contain increased concentrations of transuranics.

Operation: **Removing radioactive materials from equipment parts by spraying**
Workmen: **Operators**
Building: **C-400**

Summary of operation:

Operators were exposed to unknown quantities of internal and external emitters. The main problems were from cleaning the transfer cylinders, ash receivers, hoppers and some components of the UF_4 conversion system. They were also exposed to nitric, sulfuric and chromic acid, trichloroethylene and soda ash. Finally, there was a certain amount of exposure to various fluoride compounds, particularly during the cascade upgrade programs.

Potential for increased radiation exposure:

May have been high.

Description:

The spray booth area encompassed a number of operations. The obvious one was apparently a large well ventilated hood, where equipment items which were brought in, were sprayed to remove grease and oxides. There were apparently several spraying apparatus available, of which the most important ones were trichloroethylene, 2% sulfuric or nitric acid or a dilute soda solution. The items to be cleaned were placed in the spray booth and then treated with a high-pressure spray. If this was not adequate, then the operator would be required to scrape or brush

down the item to remove the deposit. One woman reported that the acid fumes from this operation would get so high that they would dissolve the nylons that she wore.

Respirators were apparently required, but one worker reported that his peers made fun of him because he was conscientious about wearing his. The woman mentioned above stated that the respirators used were the paper masks used in surgery operations.

Associated with the spray booth were tables where small items would be placed for hand cleaning. There was also an area in front of the building where large items were dumped until they quit giving off gases or the spray booth personnel were ready to process them. Another item associated with the spray booth was a number of vats containing various solutions, which equipment components would be placed in for soaking off difficult to remove detritus. Chromic and sulfuric acid were used in some of these vats. One of the more interesting jobs performed in the spray booth was the dismantling of the ion exchange columns which had been used apparently for isolating neptunium and technetium. The ash receivers from C-410 would be sent over. Since this was often off gassing and smoking, they would be placed in a large receiver that had a big vacuum on one end of it. The ash receivers would then be cleaned in the spray booth. They also cleaned the UF_4 hoppers from C-410.

A final aspect of this particular job is that the personnel who handled this area were on call to clean up spills, wash out items of equipment and piping, remove green salt from flanges, etc., which were too large or immobile to move to C-400. The requirement for this job was to be able to get your arm in and be able to see what was being cleaned. An air supply was provided if the end of the pipe was closed. If both ends were open, ambient ventilation was considered to be adequate. The dirty water from these operations was emptied into the spray booth.

The spray solutions were periodically tested for some unknown parameters. When the solutions reached a certain level, they were drained and replaced with fresh spray solution. The dirty solution was run through a dissolver process. This was a rotary filter with a vacuum unit. Some chemicals were mixed in which would result in the formation of a cake. The salvaged uranium would then be placed in drums. The liquid would tested for pH and uranium content. If it was within acceptable limits, then it would be run into a ditch. If not, it was run through the process again.

In addition to the main spray booth in C-400, smaller spray booths were located in C-409 and C-720. The one in C-720 was probably used mainly to remove grease and other dirt from compressor parts although, on occasion it may have be used for oxide removal. The spray booth in C-409 was used in the initial stages of tearing down converters. The waste from this spray booth was piped over to C400 for removal of uranium oxides. It is not clear, but apparently the C-409 spray booth was operated by C-400 personnel.

Items of interest include the claim by one worker that most of the time the concentrated acids were not diluted. This claim appears to be fantastic and probably not true.

Training for the spray booth consisted of having an experienced worker show the initiate how to do the job and then telling him to call him if any problems developed. Nothing formal was said about the potentials for increased radiation exposure.

References:

D01CD116. Laborer. 746A, 400, 410. 1955-1992.
D03CD029. Chemical operator. 400, 409. 1975-1978.
D03CD133. Unknown. Unknown. 1975.
D04CD055. Chemical operator. 400. 1953-1968.
D07CD007. Chemical operator, Eng. Assist. 400, cascades, 720. 1975-.
D07CD027. Power and utilities. 400, all. 1953-1979.
D24CD045. Chemical operator, Supervisor. 410, 340, 400. 1987-.
D14CD010. Maintenance. Unknown. 1972-.
D15CD138. Technician, Waste Manager. 400, cascade upgrade. 1981-.
D16CD122. Supervisor. Unknown. 1976-.
D10CD033. Feed operator. 410, 400, 340. 1952-.
D12CD035. Error.
D13CD052. Chemical operator. 400, 335, 410. 1952.

Operation: Flange grinding
Workers: Maintenance mechanics and machinists
Buildings: Cascades, C-720

Summary of operation:

Contaminated material would build up on various joints which was removed by grinding, either in situ or at the machine shop

Potential for increased radiation exposure:

Probably moderate, especially since it was a short-term job that wasn't done very often.

Detailed Description:

UF_4 and other materials would build up on surfaces and would have to be removed during maintenance and repairs.

Operation: **Green salt sweeping and drumming**
Workers: **Operators and janitors**
Buildings: **C-400, C-410, C-420, C-340**

Summary of operation:

Cleanup of spills that occurred.

Potential for increased radiation exposure:

Probably moderate.

Detailed Description:

Accidental spills of green salt were quite common in the above buildings. When they occurred, the material would be swept up and shoveled into barrows. Vacuum cleaners were supposed to be used but apparently this usually wasn't the done. On some occasions, such as when barrels were spilled at the pulverizer, the dust was thick enough that it was simply shoveled. Respirators were supposed to be used but compliance was inconsistent.

Operation: **Disassembly of compressors and block valves**
Workmen: **Maintenance mechanics, compressor mechanics**
Buildings: **Cascades, C-720**

Summary of operation

Quite frequently, there would be a UF_6 gas release when compressors or block valves were being disassembled.

Potential for increased radiation exposure:

Possibly moderate for the mechanics, less so for workers in the adjacent areas.

Detailed Description:

Whenever work was done on compressors or block valves, they were supposed to be vented first. This may have always happen and some releases may have occurred when they were being disassembled, either in situ or in the shops. The compressor shop was in on end of Building C-720. Its first level was in a pit while the room was several stories high. In extreme cases, a vapor cloud would envelop the maintenance mechanics so that they were hidden from view and would rise for several stories after which it would diffuse out into the remainder of the building that was the machine shop. The furthest the dust is reported to have reached was the center of the building where the supervisory offices were located.

Apparently, the compressor mechanics usually wore respirators when opening compressors for the first time. This minimized the potential for exposure to them. Other people working in the building would see the release and would immediately move to the opposite end of the building until the dust settled.

Operation: **Fluorine cooling tower carpentry**
Workmen: **Carpenters**
Building: **C-340**

Summary of operation:

On at least one occasion the carpenters were called in to tear down and replace the wooden portions of the fluorine cooling tower which was apparently covered with radioactive dust.

Potential for increased radiation exposure:

Possibly moderate at time of exposure. Minimal in the long run because this type of job wouldn't need to be done very often.

Detailed Description

Few details on this operation were found.

References:

Phase II report summary table

Operation: **Baghouse cleaning for cascades, C-310, C-315**
Workmen: **Operators**
Buildings: **C-331, C-333, C-335, C-337**

Summary of operation:

This operation was the same as that for C-400, C-410, C-420 and C-340. The major differences were there was likely less risk of exposure to transuranics and the volume of dust would have been considerably less.

Potential for increased radiation exposure:

Probably moderate.

Detailed Description:

The same as for C-400, C-410, C-420 and C-340.

Operation: **Instrument maintenance**
Workmen: **Instrument mechanics**
Buildings: **Cascades, C-400, C-410, C-420, C-340, C-310, C-315**

Summary of operation:

Releases of trapped gas were a frequent occurrence while maintaining instruments.

Potential for increased radiation exposures:

Probably moderate or perhaps high, depending on location and specific equipment.

Detailed Description:

There were frequent gas releases from instruments being serviced.

Operation: **Machine Shop**
Workers: **Machinists**
Building: **C-720**

Summary of operation:

There were a number of operations performed in or adjacent to the machine shop that had potential for contaminating the machinists.

Potential for increased radiation exposure:

Probably low.

Detailed Description:

There were occasions on which the personnel in the machine shop were exposed to radioactive materials. The most dramatic example was possible exposure during releases of UF_6 that occasionally occurred in the compressor pit (see disassembly of compressors and block valves above). When this happened, there would be uranyl fluoride fallout in the adjacent machine shop areas. Exposure was probably minimal due to the practice of the machinists moving to the opposite end of the machine shop when releases occurred.

There was one known exception to this practice which occurred when a machine shop supervisor ordered his workers back to work after calling the health physicist, who assured him over the phone that the dust was harmless.

Another potential for exposure was due to machining depleted uranium in the machine shop. Exposure from this source was probably minimal because of the need to keep the uranium cool

with lubricating oil to prevent magnesium type fires. Finally, there was potential exposure to dust when radioactive deposits were removed from equipment components by grinding.

A caveat that needs to be emphasized here is that machine shops are clean places. Dust would not be allowed to accumulate because of potential damage to the machine shop equipment.

Operation: Electrical work
Workmen: Electricians
Buildings: All

Summary of operation:

On occasion, electricians were exposed to excessive amounts of dust.

Potential for increased radiation exposure:

Probably low unless they were working in areas that contained TRUs in the dust or equipment.

Detailed Description:

There were occasions where electricians were exposed to excessive amounts of dust while working in dirty places. This was particularly so when they blew dust off of equipment so that they could work on it. Some wipe tests in some locations do show excessively high amounts of TRUs.

Operation: Product withdrawal during normal operations
Workmen: Operators
Building: C-310, Product Withdrawal Building

Summary of operation:

This is where enriched UF_6 product was removed from the cascade in the form of UF_6 gas and put into cylinders for transport (97-10-01). Potential radiation exposures were due to puffs of gas that sometimes occurred when the connection between the cylinders and the UF_6 pipeline were broken without adequate purging. Also, there were at least three instances where coupling between the cylinder and the gas line was broken, releasing large amounts of gas into the atmosphere (81-03-01). Primary exposures were uranium (UO_2F_2) and ^{99}Tc. Some previous hazard mapping reported these were medium and low exposures (97-10-01). The workforce consisted of operators (3-7/shift), maintenance mechanics (4/shift), instrument mechanics (2/shift), electricians (2/shift) and foremen (4/shift) (97-10-01) or 1-3 persons with a crane operator on call should crane operations involving heavy equipment be required (81-03-01).

Potential for increased radiation exposure:

There may have been increased potential for exposures to TRUs when compared, for example, to building C-315. One report indicated about 20 dpm/m3 from individual puffs based on tests run by environmental committee. Maximum allowable is 200 dpm/m^3. When there were large spills, the premises were evacuated. The release of HF posed a serious potential for chemical exposure, as it is a very strong and caustic acid. The amount of UO_2 that would be incorporated would likely be very small because of the acid. Essentially, for every molecule of UO_2F_2 released into the atmosphere, there were four molecules of HF. The HF was enough to see to it that everyone left the premises immediately.

Detailed Description:

The following material was largely excerpted from Ref. 81003-01. The C-310 Product Withdrawal Building was approximately 53 x 30 feet in size and contained two roll-up doors, one employee access door and double doors to the storage room. The building was equipped to handle two 10 to 14 ton cylinders at a given time (Fig. F-1).

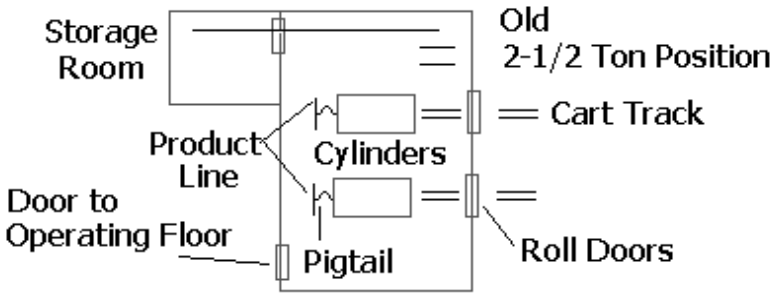

Figure F-1. Schematic diagram of Building C-310 Product Withdrawal Area.

See Appendix C for a detailed description of the operations performed in these buildings. There were two conditions under which UF_6 was released into the air. (1) A puff of UF_6 was experienced during the normal disconnect process, i.e., disconnecting the pigtail from the cylinder following the purge procedure. The puff occurred in those cases where the pigtail had been inadequately purged. (2) Large releases occurred when the pigtail line broke loose from the cylinder, for example, when the cylinder was moved before the pigtail was disconnected. Such releases occurred at least three times during the 1950's and 1960'2. When they occurred, the premises were immediately evacuated and remedial work was done by individuals in combat masks. Obviously, such spills were catastrophically expensive and were not ignored by management.

When exposed to air, UF_6 forms one molecule of uranyl fluoride and four molecules of HF gas. Worker protection from uranyl fluoride was felt to be the overriding consideration; to assure comfort as well as protection for the small puff case, half-face respirators were specified and required. It appears, however, that use of such respirators was generally left to the discretion of

the workers. In the case of large releases, full-face respirators equipped with canisters were readily available and required.

References:

#: 81-03-01

Title: Investigation of the Radiological Safety Concerns and Medical History of the late Joseph T. Harding, Former Employee of the Paducah Gaseous Diffusion Plant
Sponsor/publisher: Acting Assistant Secretary for EPS and Emergency Preparedness
Author: E. J. Vallario, H. R. Wolfe M.D.
Date: March 1981

#: 97-10-01

Title: Former Worker Medical Surveillance Program at Department of Energy Gaseous Diffusion Plants, October 1, 1997

Operation: Tails withdrawal during normal operations
Workmen: Operators
Building: C-315, Tails Withdrawal Building

Summary of operation:

This is where the depleted UF_6 tails were removed from the cascade in the form of UF_6 gas and put into cylinders for transport (97-10-01). Potential radiation exposures were due to puffs of gas which sometimes occurred when the connection between the cylinders and the UF_6 pipeline were broken without adequate purging. Also, there were at least three instances (C-310 and C-315) where coupling between the cylinder and the gas line was broken, releasing large amounts of gas into the atmosphere (81-03-01). Primary exposures were uranium (UO_2F_2). Previous hazard mapping reported these were high exposures (97-10-01). The workforce consisted of operators (2-3/shift), maintenance mechanics (4/shift), electricians (2/shift), janitor (1/shift) and foremen (4/shift) (97-10-01) or 1-3 persons with a crane operator on call should crane operations involving heavy equipment be required (81-03-01).

Potential for increased radiation exposure:

Because depleted UF_6 contained very low levels of TRUs, the potential for exposure was lower than for Building C-310.

Since the tails could contain higher levels of transuranics than the product, this process would have a higher exposure potential.

Detailed Description:

See Appendix C for a detailed description of this building. The same general conditions applied here as for building C-310, except that the levels of TRUs were probably low.
The following material was largely excerpted from Ref. 81-03-01. Much of it is repeated in the document for the Product Withdrawal Building.

The C-315 Tails Withdrawal Building was approximately 53 x 30 feet in size and contained four cart tracks and product equipment to accommodate four 10 to 14 ton cylinders. Four roll-up doors were located in the east wall to permit the entry and exit of the cylinders (Fig. F-2). The west wall contained doors to the pump room and control room. Thus, there were six penetrations (doors) affecting air current flow in the building.

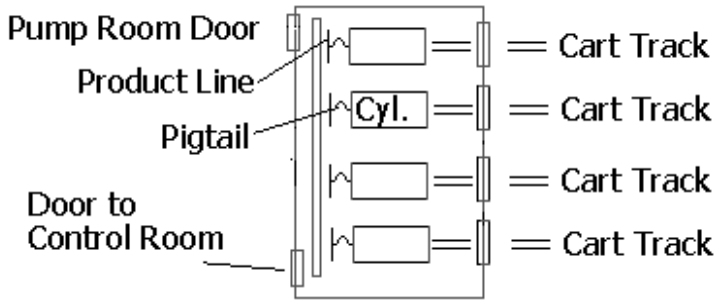

Figure F-2. Schematic diagram of Building C-315 Tails Withdrawal Area.

The operations in Buildings C-310 and C-315 were quite similar. The major difference for our purposes was that the concentrations of transuranics are higher in the withdrawal tails from C-315 than from the withdrawal product from C-310 and hence, presented a higher potential for exposure.

The liquefaction was accomplished by compression of the UF_6 flowing to the building from the enrichment operation (Buildings C-331, C-333, C-335, C-337) at a pressure which the UF_6 gas could be liquefied. After condensing, the liquid was allowed to flow into the cylinders. The product was drained as a liquid into the multi-ton cylinders through a copper tube referred to as a pigtail (note the drawing above). When the cylinder was filled to its capacity, the cylinder and drain valves were closed and the pigtail was evacuated and purged. The pigtail was then disconnected at the cylinder valve. Figures showing the pigtail and a gas cylinder mounted on a track cart can be seen in #81-03-01.

The C-315 Building began operation in early 1953. At that time, the ventilating system provided approximately 800 cubic feet/minute (CFM) exhaust in three registers near the floor along the west wall and 400 CFM of supply discharged about 9 feet above the floor from four registers. Other make up air entered from the control room and through an opening in the east wall. The

system was modified two months later by extending the local exhaust ducts to hood installed above the pigtail connections.

The building was normally manned by 1-3 persons with a crane operator on call should cylinder transfer involving crane movements be required. The workers were responsible for completing equipment checks, logging equipment data, preparing cylinders for filling, disconnecting and weighing the full cylinders, transferring cylinders, and maintaining cylinder records.

Building C-315 was basically the same (1980) structurally as it was in the 1950's. However, equipment changes have been made over the intervening years that make it difficult to determine safety conditions in the 1950's by evaluating practices used today. The most significant changes include: (1) changes to the purging system to enhance efficiency which minimizes the "puff" during the disconnect procedure; (2) the installation of an "interlock" system to prevent the withdrawal of the cylinder before the pigtail has been disconnected. In the early 1950's before the interlock system was installed, at least three major releases resulted from cylinders being withdrawn while still connected to the pigtail.

An experiment was conducted (1981) to emulate the conditions that existed in the 1950's. The reader is referred to #81-03-01 for the details of how this was the done.

From the above, it can be seen that there were two conditions under which UF_6 was released into the air. (1) A puff of UF_6 was experienced during the normal disconnect process, i.e., disconnecting the pigtail from the cylinder following the purge procedure. The puff occurred in those cases where the pigtail had been inadequately purged. (2) Large releases occurred when the pigtail line broke loose from the cylinder, for example, when the cylinder was moved before the pigtail was disconnected. Such releases occurred at least three times during the 1950's and 1960'2. When they occurred, the premises were immediately evacuated and remedial work was done by individuals in combat masks.

Worker protection from uranyl fluoride was felt to be the overriding consideration; to assure comfort as well as protection for the small puff case, half-face respirators were specified and required. It appears, however, that use of such respirators was generally left to the discretion of the workers. In the case of large releases, full-face respirators equipped with canisters were readily available and required.

References:

#: 81-03-01

Title: Investigation of the Radiological Safety Concerns and Medical History of the late Joseph T. Harding, Former Employee of the Paducah Gaseous Diffusion Plant
Identifier (sponsor/publisher): Acting Assistant Secretary for EPS and Emergency Preparedness
Authors: E. J. Vallario, H. R. Wolfe M.D.
Date: March 1981

#: 97-10-01

Title: Former Worker Medical Surveillance Program at Department of Energy Gaseous Diffusion Plants, October 1, 1997

Operation: Crawling the pipes
Workmen: Operators, welders
Buildings: C-331, C-333, C-335, C-337 (cascade buildings)

Summary of operation:

The cascades were a series of stages, each of which consisted of a converter, a compressor, pipes, valves and related equipment. The converters were used to increase the amount of ^{235}U present in UF_6 gas that was fed into the system. Since the system was under negative pressure, the potential for increased radiation exposure was usually negligible except for any dust that got into the air and any exposure received by operators and maintenance mechanics while removing equipment from the cascades and crawling the pipes to make sure they are clean. Crawling the pipes was done during repair and maintenance operations, cell replacement and the cascade upgrade programs. The problem with pipe crawling was the formation of a uranyl fluoride powder on the inside surfaces of the cells shortly after the cell was opened and exposed to moisture in the atmosphere.

Potential for increased radiation exposure:

There was a potential for exposures, depending if aerosols were created and if the use of respirators was adequate. There may have been some potential for exposures to betas and gammas.

Detailed Description:

See Appendix C for a detailed description of these buildings.

The basic component of a cascade cell was a single converter (Fig. F-3). It consisted of a cylindrical tank (2 sizes) with an input line and two output lines. The enriched output line contained a product that had a slightly greater content of ^{235}U than the input line, while the depleted output line had a slightly lower concentration. By hooking a series of converters together, it was possible to get an output containing about 3% ^{235}U compared to about 0.5% ^{235}U starter material.

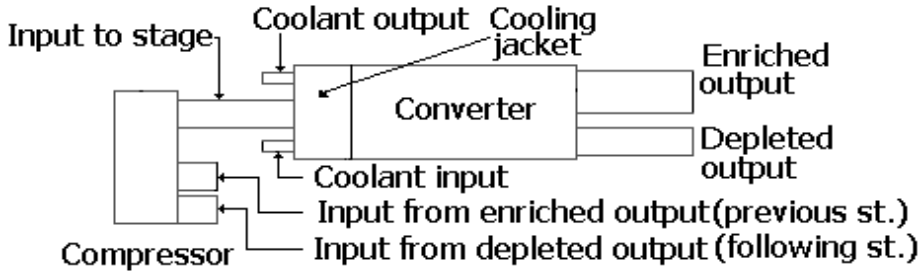

Figure F-3. Schematic layout of a cascade converter or cell with associated compressor. The control valves are not shown.

The front end of the converter consisted of a cooling jacket composed of coils through which cooling gas (freon) was continuously fed to reduce the temperature of the UF_6 prior to entering the converter proper. The working component of the converter was a porous, nickel tube through which ^{235}U would diffuse slightly faster than could ^{238}U.

UF_6 at room temperature is a solid. It sublimates at 53 deg C to form a gas. Heat is required to keep it in a gaseous state. The pressure of the UF_6 gas is increased prior to entry into the converter by a large compressor. This compressor has two input lines and one output line. The output line goes directly to the converter. One of the input lines contains enriched output from the previous converter. The other input line contains depleted output from the next converter in the series. This pipe had a diameter of 42 inches and was large enough to crawl in.

Not shown in the figure are a number of shutoff valves that were used to control flow into and out of the converter. The compressor was connected to the lines by welded flange joints. On long lines, there were access holes (the reference stated "cut a hole in the side of the pipe") which could be opened to allow worker access. Access could also be achieved by removing sections of pipe.

The enrichment process is done by arranging several hundred converters into a cascade. Fig. F-4 is a simplified drawing of a five unit cascade. Note that the depleted output of each cascade reenters the system through one of the input pipes of the compressor of the previous converter. The Paducah Plant had several thousand converters housed in four buildings, C-331, C-333, C-335 and C-337. Product withdrawal was done in Building C-310 while tails withdrawal occurred in Building 315. Major fires occurred in Buildings C-337 and C-310.

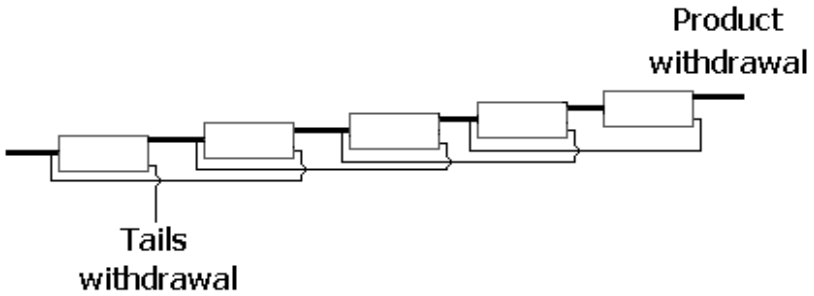

Figure F-4. Schematic layout of a cascade consisting of 5 converters.

The requirements for maintenance and repair of the cascade components necessitated that sections of the cascade be taken offline so that they can be opened up and worked upon. For this reason, there were bypass lines throughout the system.

There were several reasons why sections of the cascade would be shut down and disassembled for repair. These included:

1. Compressor deblading.
2. Maintenance.
3. Converter replacement during the cascade upgrade programs.

In the first case, which was apparently the most common, the blades on a compressor would disintegrate as a result of prolonged usage without periodic replacement. When this happened, the compressor would be removed from service and a man would be sent down the pipes to remove any debris that might be present. According to D09CD059, this operation required about 20 minutes and needed to be done about four times a year (several month intervals) for the building he worked in. He did it about once a year. This would mean that deblading was done approximately sixteen times a year if all of the cascade buildings were considered.

During the 1970's upgrade program, the system was opened and it was probable that a considerable amount of pipe crawling was done at that time (CD052). As part of the upgrade program, baffles would be welded inside of the pipes to shield the expansion joints (CD010, CD029).

The procedure for working on the converters, compressors and associated pipes was approximately as follows. First of all, the section of converters to which the affected unit belonged would be bypassed (there is a description of one case where this wasn't done). The system would then be shut down and purged of UF_6. Eventually a practice called sweeping out the UF_6 was initiated (CD41, CD59). The system would then be sampled to ensure that it was clean after which the maintenance workers would cut the compressor out or cut open an access shuttle in the pipe. This was apparently done with cutting torches by the welders. The operators (CD153, CD154, CED110) did the actual pipe crawling in the early days.

Regarding safety equipment, the operators would wear coveralls. Other items which may not have been used in the beginning was to wrap exposed skin with towels and apply an ointment (FEND) as a barrier against HF. The cuffs and sleeves would be taped (CD038). The ointment was messy and may not have been used much. Other items were safety shoes (possibly used with a cover) and a skullcap (CD153, CD154). Respirators were recommended, but often not used (CD10, CD29, CD58), especially if the worker was only going to be in the pipe for a short time. The original respirator was an army combat mask that most workers knew how to use because they had been in the military.

Over the years, the protective equipment evolved until nowadays, the worker dons a special pair of coveralls and has a respirator with its own air supply (CD28, CD38). A safety rope was put around the workers waist so that he could be hauled back if there were difficulties (CD087, 059).

After the worker completed the pipe crawling task, his cloths would be covered with a gray dust (CD058). The worker usually went to the locker room, changed clothes, took a shower, don clean clothes and return to work. If the worker didn't get very dirty, this might be skipped (CD038). There is no mention of urinalysis being done after crawling the pipes.

References:

The Gaseous Diffusion Process, DOE Report #ORO-684.

D03CD29
D04CD047
D06CD132
D07CD032
D08CD095
D09CD028
D09CD059
D12CD035
D12CD051
D12CD097
D15CD058
D18CD087
D20CD110
D20CD121
D23CD041
D24CD038
D26CD154
D27CD153
D27CD151

Operation: **Midnight negatives**
Workmen: **Everyone outside the cascade buildings**
Buildings: **Air content in the vicinity of the cascade buildings**

Summary of operation:

The practice of using the building air lines to flush the contents of a cell into the outside atmosphere via the exhaust stacks of the cascade buildings. The objective was to get a negative reading for UF_6 gas so that the workers could perform maintenance work.

Potential for increased radiation exposure:

Probably low for the workers involved, but it did vent UF_6 into the surrounding area. Worker transcript D25CD143 estimated that 10 to 50 pounds of UF_6 would be vented into the atmosphere for each incident.

Detailed Description:

The procedure for getting a negative reading on a cascade cell was to shut off the intake valve into the cell and pump as much of its contents as possible into the cascade via the output line. Once this had been done, the cell would be isolated and filled with dry nitrogen under pressure. This apparently was apparently vented into a large surge tank. The process would be repeated at least twice. Where the contents went from this point was not stated.

Sometimes this system would not obtain a negative and the plant air system was used for the final venting. In this method, the plant air system would be used to create a vacuum in the tank and the contents would be sucked out, mixed with the air and vented through the stacks. The system was apparently comparable to using an aspirator on a water line to suction air from suction flasks in a chemistry laboratory. Since the system created a noticeable mist that was readily visible during the daytime, the practice was only done at night.

This procedure was legitimately used for HF sweeps after the cell was empty to remove residual gas. In this case the air would be clean.

The practice was most common during the years 1980 to 1985 when there was pressure for maximum production. It was apparently not very common, particularly since it was completely against the rules and had to be done without the high level managers knowing about it. Some half-a-dozen interviewees were asked about the practice and replied that they didn't know anything about it.

References:

D27CD153
D26CD148
D25CD143
D12CD051

Operation: **Fire suppression**
Workmen: **All. In at least one case, firefighters from surrounding communities were also involved.**
Buildings: **C-310, C-315, C-720**

Summary of operation:

Over the years, there have been a number of fires at PGDP. In at least one case, firefighters from surrounding communities participated [CD070].

Potential for increased radiation exposure:

Unknown

Detailed Description:

No information was obtained on these incidents

APPENDIX G

Estimated Dose Results Using ICRP 68

Estimated dose results using ICRP 68 DCFs for particle sizes of 1µ and 5µ AMAD
See Section 7.5 for dose calculation methodology.

Effective Dose **Hypothetical Worker Exposures to Np-237, Pu-239, Th-230 and U**	**FGR, No.11 CEDE in a year rem**	**1 µ AMAD ICRP 68 E in a year rem**	**5 µ AMAD ICRP 68 E in a year rem**	**FGR, No.11 CEDE in a year rem**	**1 µ AMAD ICRP 68 E in a year rem**	**5 µ AMAD ICRP 68 E in a year rem**
	Based on Average Air Concentrations			Based on Maximum Air Concentrations		
Control Room, C-410	0.09	0.05	0.03	0.46	0.24	0.16
Green Salt Plant, C-420	0.12	0.17	0.11	1.62	2.24	1.45
Cold Trap	0.10	0.05	0.04	0.50	0.27	0.18
Fluorination Tower, C-410	0.47	0.21	0.15	5.90	2.66	1.86
Powder Handling, C-410, C-420	0.58	0.17	0.13	9.37	2.80	2.11
Ash Receivers	0.56	0.24	0.17	10.85	4.60	3.18
Total	**1.92**	**0.90**	**0.63**	**28.70**	**12.81**	**8.95**
Pulverizer	0.24	0.10	0.07	8.68	3.68	2.54
Converter Salvage Line, C-400	8.20	1.45	1.04	91.93	15.52	11.12
Total	**8.44**	**1.55**	**1.11**	**100.61**	**19.20**	**13.66**
Converter Maintenance	**0.73**	**0.11**	**0.08**	**7.33**	**1.08**	**0.78**

Lung **Hypothetical Worker Exposures to Np-237, Pu-239, Th-230 and U**	**FGR, No.11 CDE in a year rem**	**1 µ AMAD ICRP 68 H_t in a year rem**	**5 µ AMAD ICRP 68 H_t in a year rem**	**FGR, No.11 CDE in a year rem**	**1 µ AMAD ICRP 68 H_t in a year rem**	**5 µ AMAD ICRP 68 H_t in a year rem**
	Based on Average Air Concentrations			Based on Maximum Air Concentrations		
Control Room, C-410	0.11	0.16	0.11	0.54	0.80	0.53
Green Salt Plant, C-420	1.09	1.59	1.04	14.12	20.64	13.52
Cold Trap	0.14	0.21	0.14	0.72	1.07	0.70
Fluorination Tower, C-410	0.28	0.42	0.28	3.45	5.21	3.50
Powder Handling, C-410, C-420	5.69	1.68	0.99	92.51	27.27	16.14
Ash Receivers	0.18	0.28	0.19	2.09	3.43	2.32
Total	**7.49**	**4.34**	**2.75**	**113.42**	**58.43**	**36.72**
Pulverizer	0.08	0.12	0.08	1.67	2.74	1.86
Converter Salvage Line, C-400	0.97	1.56	1.04	10.70	17.24	11.37
Total	**1.05**	**1.68**	**1.12**	**12.38**	**19.99**	**13.23**
Converter Maintenance	**0.08**	**0.13**	**0.09**	**0.82**	**1.32**	**0.87**

Bone Surface **Hypothetical Worker Exposures to Np-237, Pu-239, Th-230 and U**	**FGR, No.11 CDE in a year rem**	**1 µ AMAD ICRP 68 H_t in a year rem**	**5 µ AMAD ICRP 68 H_t in a year rem**	**FGR, No.11 CDE in a year rem**	**1 µ AMAD ICRP 68 H_t in a year rem**	**5 µ AMAD ICRP 68 H_t in a year rem**
	Based on Average Air Concentrations			Based on Maximum Air Concentrations		
Control Room, C-410	1.62	1.20	0.81	8.09	6.00	4.03
Green Salt Plant, C-420	0.27	0.26	0.19	3.48	3.34	2.41
Cold Trap	1.68	1.26	0.85	8.40	6.28	4.23
Fluorination Tower, C-410	8.62	6.40	4.30	107.81	79.96	53.79
Powder Handling, C-410, C-420	0.14	0.14	0.10	2.32	2.23	1.61
Ash Receivers	11.42	9.63	6.51	225.98	192.56	130.12
Total	**23.75**	**18.88**	**12.75**	**356.08**	**290.37**	**196.19**
Pulverizer	4.88	4.12	2.78	180.78	154.05	104.10
Converter Salvage Line, C-400	182.76	65.85	45.28	2057.56	719.31	495.14
Total	**187.64**	**69.97**	**48.06**	**2238.34**	**873.36**	**599.24**
Converter Maintenance	**16.37**	**4.87**	**3.36**	**163.66**	**48.68**	**33.63**